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The Quaternary Evolution of the Rio Alias southeast Spain, with Emphasis on Sediment Provenance

Thesis submitted in accordance with the requirements of the University of Liverpool for the degree of Doctor in Philosophy, by Elizabeth Maher

December 2005

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Abstract: The Quaternary Evolution of the Rio Alias southeast Spain, with Emphasis on Sediment Provenance

This study aims to determine the late-Quaternary evolution of an ephemeral, transverse river system developed in southeast Spain, with particular reference to sediment provenance variation. The Rio Alias drains two inter-montane east-west orientated Neogene sedimentary basins; the Sorbas and Almeria basins. Pliocene to present transpressional tectonics has led to inversion of the sedimentary basins and incision of the developing fluvial system. Fluvial incision has led to the preservation of a suite of alluvial terraces recording the late-Quaternary development of the Rio Alias. Fluvial system inauguration began in the Plio-Pleistocene epoch. The primary fluvial system developed as a consequent river later becoming superimposed and transverse to structure.

The drainage basin of the Rio Alias has been sub-divided into 4 sub-basins; The Lucainena, Polopos, Argamason and El Saltador sub-basins. Each basin is structurally controlled. The impact of climate, tectonics, river-capture and eustatic sea-level variation on the fluvial system evolution varies both spatially and temporally across the sub-basins of the Rio Alias. Across the region alluvial aggradation is thought to relate to global glacial periods and incision to interglacial periods.

The Lucainena sub-basin is largely controlled by climatic variation related to glacial interglacial cycles with slight modification due to local small scale river-capture and regional epeirogenic uplift. The Polopos sub-basin is also largely controlled by climatic variation, however a major river-capture event c.70ka beheaded the Rio Alias of c.70% of its drainage area. Following the loss of drainage the beheaded Rio Alias system lost stream power, this is reflected in the decrease in size of bedform geometry and the reduced incisional capacity of the fluvial system of the post-capture terrace sequence. In the Argamason sub-basin the Rio Alias crosses the Carboneras Fault Zone, a left-lateral strike slip fault. Late-Quaternary tectonic activity has significantly modified the climatically generated signal. Large tortuous meanders developed in response to normal tectonic activity and continued tectonically driven base-level lowering led to abandonment of terraces and local incision. The El Saltador sub-basin is located at the seaward end of the system and the climate generated phases of aggradation and incision have been greatly complicated by eustatic sea-level variation related to glacial/interglacial cycles. The lowering of base-level due to sea-level regression initially led to pronounced incision along steep gradients and to the development of meander loops in the seaward end of the Rio Alias, during what regionally was a climate driven phase of aggradation.

Analysis of the alluvial sediment using a combination of field based clast analysis and laboratory analysis (petrology, SEM, magnetic analysis) allows a detailed picture of sediment provenance variation to be established throughout the evolution of the Rio Alias. Provenance analysis provides information on the timing and extent of river-capture related loss of drainage area, the relative timing of local tectonic activity and also provides new information regarding sediment source area variation throughout the development of the fluvial system. Detailed analysis of the terrace sediments and the modern channel indicates that as the fluvial system incises, local input of sediment from the steepening valley sides grows increasingly dominant. The coupling between the hillslopes and the channel thus changes through time. Sediment provenance analysis has increased our understanding of the long-term fluvial evolution of the Rio Alias, identifying not only sediment provenance variation due to river-capture and changing geology but to fluvial system development.

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1.1 Introduction

Palaeoenvironmental reconstructions in fluvial systems are often based on patterns of sediment provenance within the sedimentary record. Detailed analysis of the lithological/mineralogical assemblage of alluvial sediments enhances our understanding of drainage evolution by allowing inferences to be made regarding variations in source area characteristics, and consequently drainage reorganisation. Furthermore a combined approach to sediment provenance analysis involving both the bedload and suspended load, could allow observations to be made related to fluvial process. The Rio Alias (Figure 1.1) of southeast Spain provides an excellent opportunity to study the Quaternary evolution of an ephemeral fluvial system, affected by both climatic and tectonic variations. Throughout the Almeria region major periods of aggradation and incision during the Quaternary are thought to relate to climatic fluctuations. Such major aggradational and dissectional phases can be identified through the river terrace sequence preserved within the drainage of the Rio Alias. The Rio Alias however, also holds detailed information regarding relatively recent tectonic activity and a major river capture events on a regionally significant scale.

The lithologically diverse catchment of the Rio Alias lends itself to studies regarding sediment provenance variations, and as such river capture events, tectonic pulses and even changes in alluvial style can be attributed to individual phases of system development. Provenance analysis of both the fine and coarse component of the alluvial deposits allows inferences to be made regarding the differential aspects of suspended sediment and bedload transport mechanisms, as well as recording the effects of both regional and local scale river capture events.

1.2 Study Aims

This study aims to address changes in alluvial system development through a combination of field mapping and laboratory techniques. The main aims are as follows:

- To resolve the Quaternary evolution of the Rio Alias in terms of eustatic, tectonic and climatic controls.
- Assess the role of sediment provenance variation as a diagnostic tool for identifying periods of drainage re-organisation within the geomorphological record.
- Assess the validity of environmental magnetism, petrological and SEM analysis as sediment-source ascription tools for analysis of the suspended load in a semi-arid fluvial environment.
- Determine the impact of drainage re-organisation events on alluvial system development.
- Identify any possible periods of tectonic activity (particularly those related to the Carboneras Fault Zone, see below) and their influence on fluvial development.

1.3 Regional Context

1.3.1 Introduction

The Rio Alias is an ephemeral, transverse fluvial system developed within the basin and range setting of Almeria province (Fig. 1.1). Almeria is the eastern-most province of Andalucia, and lies at a latitude of 37°N. The area is characterised by a modern semi-arid climate with a mean monthly temperature range of 15°C (January) to 40°C (July/August) and mean annual precipitation values of less than 300mm. The region is tectonically active, with several historical earthquakes recording large-scale movements of the major fault zones (the town of Vera was all but destroyed in an earthquake during the last century (Mather et al., 2001)).

1.3.2 Tectonic History

Almeria province lies within the Betic Cordillera which along with the Moroccan Rif form the western part of an Alpine Mountain chain created by the collision of the European/Iberian and African lithospheric plates from late Mesozoic times (Monie et al., 1991). The collision saw the emplacement of nappes onto the External Zones of the cordillera, whilst the Internal Zones are characterised by a stack of thrust sheets of deformed Palaeozoic and Mesozoic dominantly metamorphic rocks. A series of interconnected Tertiary sedimentary basins are located within the Internal Zone. The Rio Alias is located within the Sorbas and Almeria basins (Figure 1.2).

Around 11 million years ago transpressional strike-slip tectonics began to dominate the neotectonic patterns of the Internal zone of the Betic Cordillera (Bousquet, 1979; Sanz de Galdeano, 1990) associated with the continued interaction of the Iberian/African lithospheric plates. Compression is taken up along the Palomares and Carboneras fault zones (Figure 1.2), major left-lateral strike-slip faults that form part of the larger Trans-Alboran Shear Zone (Larouziere et al., 1988; Montenat et al., 1987b). These faults helped define the Neogene sedimentary basins and dominate the neotectonics of the area, creating a series of locally uplifted mountain blocks and locally downfaulted sedimentary basins (Sanz de Galdeano, 1990). Local patterns of compression/extension are extremely complex (Keller et al., 1995). Tectonic activity has continued throughout the Pliocene/Pleistocene, with the Sorbas and Almeria basins subjected to compression, uplift and dissection (Mather & Harvey, 1995). Oligocene nappe emplacement has led to the current situation of differential epeirogenic uplift (Braga et al., 2003) relating to the regional tectonics (Weijermars, 1985a: 1985b; Weijermars et al., 1985; Hall, 1983).

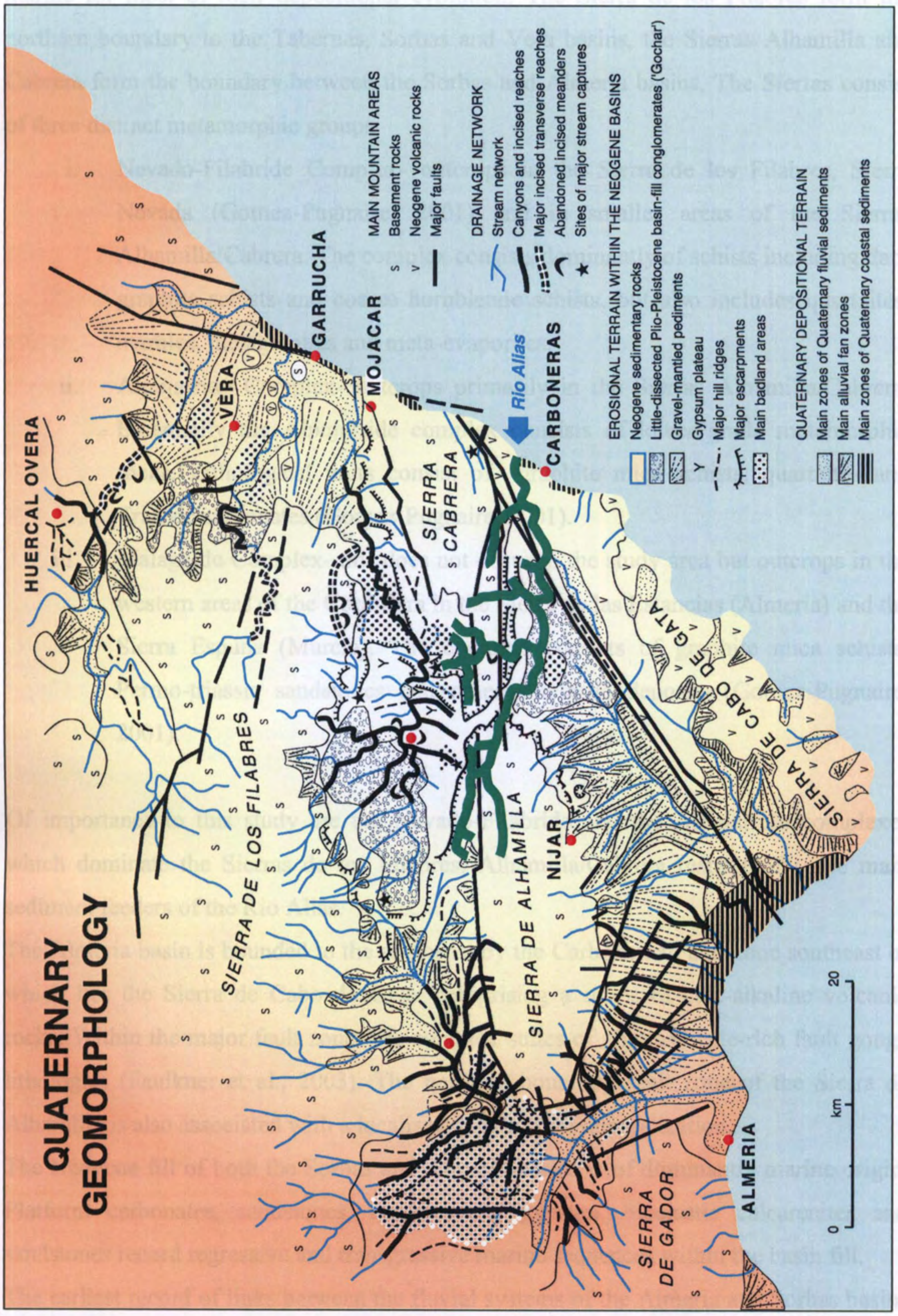


Figure 1.1 Quaternary geomorphology of southeast Spain (Adapted from Harvey, 2001).

1.3.3 Regional Stratigraphy

The Neogene sedimentary basins were defined in the Tortonian, and were to remain marine for most of their depositional evolution. The Sierra de los Filabres form the northern boundary to the Tabernas, Sorbas and Vera basins, the Sierras Alhamilla and Cabrera form the boundary between the Sorbas and Almeria basins. The Sierras consist of three distinct metamorphic groups:

i. Nevado-Filabride Complex- outcrops in the Sierra de los Filabres, Sierra Nevada (Gomez-Pugnaire, 2001) and in smaller areas of the Sierras Alhamilla/Cabrera. The complex consists dominantly of schists including dark graphite schists and coarse hornblende schists, but also includes quartzites, marbles, metagranites and meta-evaporites.

ii. Alpujarride Complex- outcrops primarily in the Sierras Alhamilla/Cabrera. Essentially the Alpujarride complex consists of lower grade metamorphic rocks. Lithological units consist of graphite mica schists, quartzites and Triassic carbonates (Gomez-Pugnaire, 2001).

iii. Malaguide Complex- this does not occur in the study area but outcrops in the western areas of the Cordillera in the Sierra de las Estancias (Almeria) and the Sierra Espuna (Murcia). The complex consists of graphite mica schists, Permo-triassic sandstones and other siliclastic deposits (Gomez-Pugnaire, 2001).

Of importance to this study are the Nevado-Filabride and the Alpujarride complexes which dominate the Sierras de los Filabres, Alhamilla/Cabrera respectively, the main sediment feeders of the Rio Alias.

The Almeria basin is bounded to the southeast by the Carboneras Fault zone southeast of which lies the Sierra de Cabo de Gata, comprising a series of calc-alkaline volcanic rocks. Within the major fault zones are complex suites of phyllosilicate-rich fault gouge lithologies (Faulkner et al., 2003). The northern boundary fault zone of the Sierra de Alhamilla is also associated with a localised zone of iron mineralization.

The Neogene fill of both the Sorbas and Almeria basins is of dominantly marine origin. Platform carbonates, sandstones, marls, reefs, gypsum, bioclastic calcarenites and sandstones record regressive and transgressive marine sequences within the basin fill.

The earliest record of links between the fluvial systems of the Almeria and Sorbas basins comes in the end basin-fill sediments of the Pliocene Gochar formation (Mather, 1991) and the Polopos formation (Mather, 1991; 1993b). This initial fluvial system was superimposed by the retreating Cariatiz Sea of the Sorbas basin, and flowed transverse to structure across the Sierras Alhamilla/Cabrera into the still marine Almeria basin. Modern drainage patterns can, as a result, be traced back to the early Pliocene and the strong links between the basins where evident even then.

1.3.4 Quaternary Drainage Patterns and the Aguas-Feos Master Stream

The development of the primary fluvial system of the Sorbas basin (Gochar Formation of Mather, 1991) during Plio-Pleistocene times (Mather, 1991) established the connection of the fluvial systems from the Sorbas to the Almeria basin, as the Rio Aguas became the master drainage of the Sorbas basin. Throughout the Pliocene and a large part of the Quaternary the Rio Aguas exited the Sorbas basin to the south cutting a transverse course across the Sierra Alhamilla/Cabrera, flowing out to the east via the Rio Alias across the Almeria basin (Harvey and Wells, 1987). Around 70,000 yrs ago (Candy et al., 2005) the Rio Aguas was re-routed to the east via the aggressive headwards erosion of the lower Aguas, the Rio Alias consequently lost more than 70% of its drainage area. The Quaternary evolution of the Rio Aguas of the Sorbas basin is well established (Harvey & Wells, 1987; Harvey et al., 1995; Mather & Harvey, 1995) and its links with the Almeria basin to the south (Figure 1.2) well documented. The fluvial evolution of the Rio Alias of the Almeria basin, and therefore the distal portions of the proto Aguas/Feos, however are poorly understood.

Climatic conditions are thought to dominate the overall depositional/incisional sequence within the western Mediterranean (Macklin et al., 2002). Quaternary glacials have been related to major periods of sediment production (Amor & Florschutz, 1964) and interglacial periods have been related to periods of incision (Harvey, 1990). The Quaternary deposits of the ancestral Aguas/Feos system (of Harvey & Wells, 1987) indicate some climatic control, as terrace deposits can be more than 20m thick in several locations. However, neotectonics throughout the region have also exerted control on the development of fluvial systems throughout the area (Harvey & Wells, 1987; Mather, 1991; Mather & Harvey, 1995; Stokes, 1997). This control is often via positioning of the developing fluvial systems, however the Rio Alias crosses several major geological structures (Figure 1.2) that have exhibited intermittent activity throughout the Quaternary (Keller et al., 1995). Finally, the distal portion of the Rio Alias has been influenced by Quaternary sea-level change.

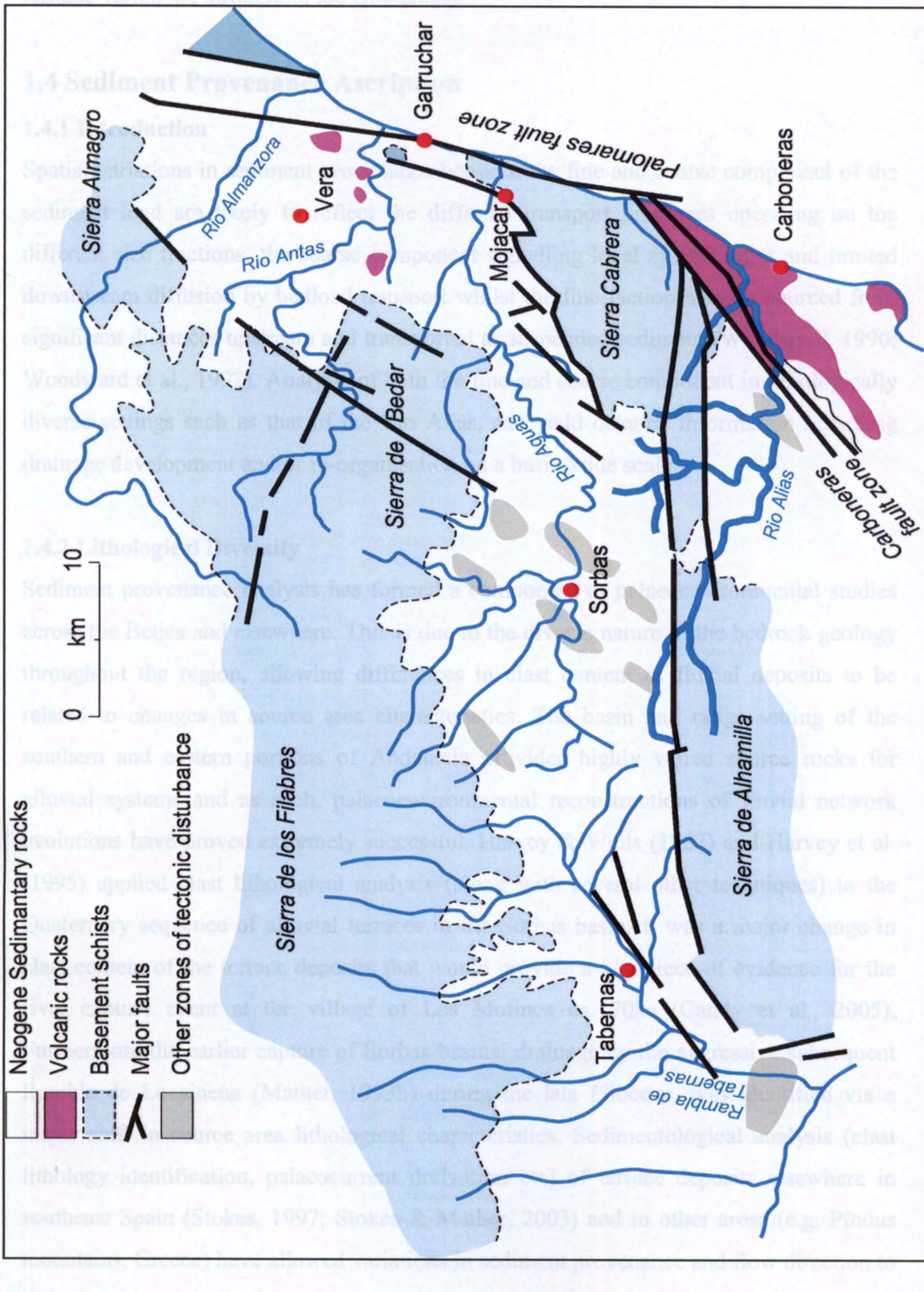


Figure 1.2. Tectonic map of southeast Spain (Based on Harvey, unpublished and Maher et al., in press)

Consequently the Rio Alias has developed under the influence of climatic, tectonic and eustatic variations throughout the Quaternary.

1.4 Sediment Provenance Ascription

1.4.1 Introduction

Spatial variations in sediment provenance between the fine and coarse component of the sediment load are likely to reflect the different transport processes operating on the different size fractions, the coarse component signalling local system input and limited downstream diffusion by bedload transport whilst the fine faction may be sourced from significant distances upstream and transported as suspended sediment (Woodward, 1990; Woodward et al., 1992). Analysis of both the fine and coarse component in lithologically diverse settings such as that of the Rio Alias, can yield detailed information regarding drainage development and/or re-organisation on a basin-wide scale.

1.4.2 Lithological Diversity

Sediment provenance analysis has formed a component of palaeoenvironmental studies across the Betics and elsewhere. This is due to the diverse nature of the bedrock geology throughout the region, allowing differences in clast content of fluvial deposits to be related to changes in source area characteristics. The basin and range setting of the southern and eastern portions of Andalucia provides highly varied source rocks for alluvial systems and as such, palaeoenvironmental reconstructions of fluvial network evolutions have proved extremely successful. Harvey & Wells (1987) and Harvey et al. (1995) applied clast lithological analysis (along with several other techniques) to the Quaternary sequence of alluvial terraces in the Sorbas basin. It was a major change in clast content of the terrace deposits that would provide a key piece of evidence for the river capture event at the village of Los Molinos ca. 70ka (Candy et al., 2005). Furthermore the earlier capture of Sorbas basinal drainage by the aggressive subsequent Rambla de Lucainena (Mather, 1993b) during the late Pliocene, was identified via a major shift in source area lithological characteristics. Sedimentological analysis (clast lithology identification, palaeocurrent derivation etc) of terrace deposits elsewhere in southeast Spain (Stokes, 1997; Stokes & Mather, 2003) and in other areas (e.g. Pindus mountains, Greece) have allowed variations in sediment provenance and flow direction to be inferred in many fluvial systems (Woodward, 1990; Woodward et al., 1992).

1.4.3 The Fine and Coarse Component

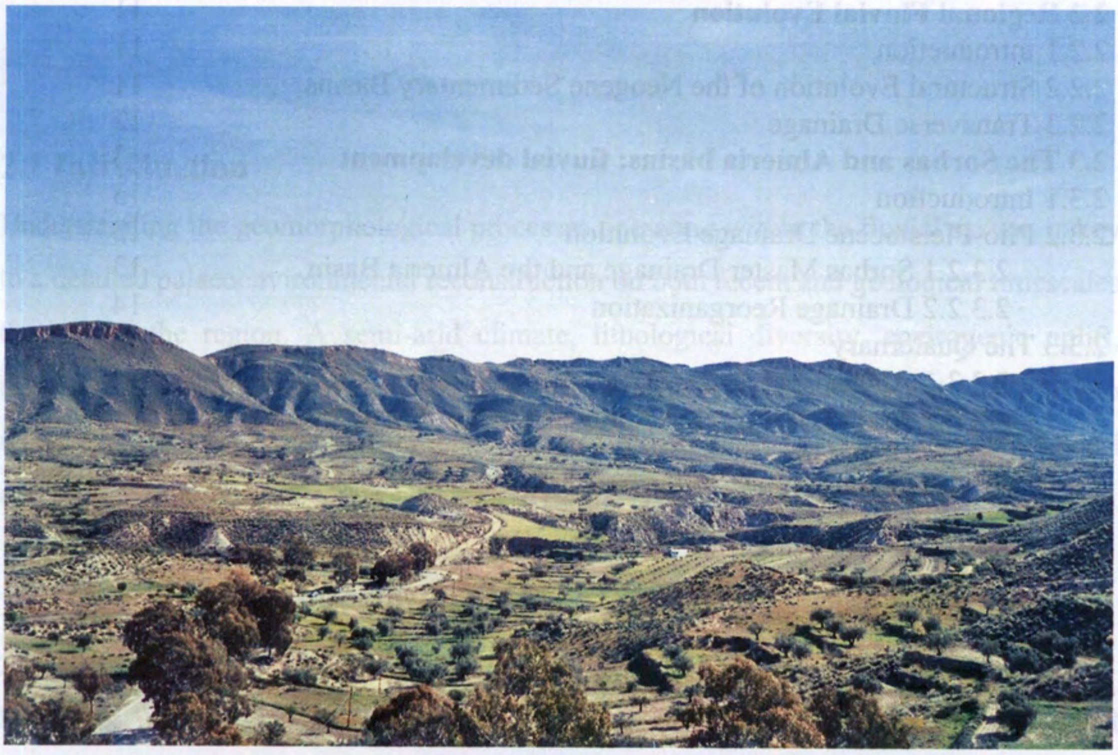
Sediment provenance variations of both fine and coarse load are key to the interpretation of such a system where we know river capture and drainage reorganisation have played a dominant role in fluvial development.

It is important to acknowledge the different mechanisms and processes operating on, and, supplying both the coarse and fine sediment loads (Woodward, 1990; Woodward et al., 1992). The sediment load of the river at any one point may therefore reflect input from spatially varied source areas (bedload reflecting local sediment input, fine sediment perhaps reflecting more widespread diffuse sediment sources). Analysis of the coarse component of the sediment load (i.e clast analysis) should reveal information regarding the provenance of the river's bedload component (B axis >2cm). Analysis of the finer fraction of the same sediments should yield information on the provenance of the suspended load (<2mm). Fine and coarse sediment assemblage differentiation may also be a function of sediment availability (i.e. resistant limestone yields coarse clasts but very little fine sediment but marl will produce only fine grained sediment). Interpretation of the sediment assemblage of any fluvial deposit is considered consequently on a particle size basis.

1.5 The Rio Alias

The Rio Alias lends itself to such a study aiming to clarify changes in sediment provenance and fluvial style throughout the Quaternary. The previous research completed within the region has put into place a framework to build upon, regarding Quaternary alluvial development. Harvey & Wells (1987), Mather (1991), Harvey et al., (1995) and Mather & Harvey (1995) have provided an understanding of the Pliocene to Quaternary development of the Sorbas basin fluvial system. However, in order to understand the evolution of this system fully the long-term drainage evolution of the Rio Alias (and hence the distal portion of the Sorbas master drainage) needs to be examined in greater detail. Through analysis of the terrace assemblage within the Alias basin, it is hoped that a greater understanding of the Quaternary development of the Rio Alias will be obtained. The lithological diversity of this area is such that it may allow fine sediment movement to be identified using laboratory techniques focused upon compositional variations. Such techniques include environmental magnetism, petrological thin section analysis and mineral determination using the Scanning Electron Microscope (SEM). Sediment provenance variations between the coarse and fine load and the degree of sediment connectivity (Harvey, 2002; Hooke, 2004) throughout the system, should allow the assessment of the impact of river capture events and substantial tectonic movements upon the evolution of this fluvial system. Studies concerning sediment provenance variations can only be attempted in locations were lithological diversity is great enough to allow the inference of provenance changes based purely upon the sediment assemblage. This study area possesses such diversity. Furthermore the variable magnetic properties of the possible bedrock sources allows an attempt to be made to evaluate the provenance of the suspended load through the application of environmental magnetism.

Chapter 2
Geomorphology of southeast Spain



Rambla del Penoncillo (Lucainena headwaters), Sorbas basin

Chapter 2
Geomorphology of southeast Spain

Chapter 2
Geomorphology of southeast Spain

2.1 Introduction

Understanding the geomorphological processes operating within the fluvial system is key to a detailed palaeoenvironmental reconstruction on both recent and geological timescales throughout the region. A semi-arid climate, lithological diversity, epeirogenic uplift, tectonic deFormation, eustatic base-level change and river capture events have led to reorganization of the regional drainage systems of southeast Spain on various temporal and spatial scales (Harvey, 1987; Mather et al., 2001).

2.2 Regional Fluvial Evolution

2.2.1 Introduction

Harvey & Wells (1987), Mather (1991) and Stokes (1997) demonstrate that modern and Quaternary drainage patterns across southeast Spain have been superimposed by the initial fluvial systems developed during Plio-Pleistocene times. Consequently in order to fully understand the behaviour, and controls upon the fluvial system throughout the Quaternary the long term dynamics of the basinal drainage must be considered.

2.2.2 Structural Evolution of the Neogene Sedimentary Basins

The Neogene sedimentary basins were defined in the Tortonian by the northeast-southwest orientated strike slip faults of the region (the Palomares and Carboneras faults; Figure1.2), the Sorbas and Almeria basins forming as part of the Alboran Sea (Comas et al., 1992). The Sorbas and Almeria basins were partially differentiated before the end of the Tortonian but a marine connection was to persist between the basins until after the end of the Messinian (Mather, 1991). The Sierras Alhamilla and Cabrera form the boundary between the two basins, whilst a structural low between the two ranges allowed the aforementioned marine connection to remain. The eastern and western margins of the

Sorbas basin are poorly defined structural highs, separating the Sorbas basin from the Vera basin to the east and the Tabernas basin to the west (Figure 1.2).

Continued differential uplift of the basins throughout the region caused the switching from marine to subaerial environments during the Pliocene. The Almeria basin was to remain marine longer than its neighbouring basins, thus becoming the only marine connection to the terrestrial Sorbas basin (Mather, 1991).

Differential uplift of the basins (Braga et al., 2003) led to tectonically induced gradients between the basins stimulating initiation of the drainage system, incision and reorganisation of regional drainage patterns (Harvey, 1987; Harvey & Wells, 1987; Mather, 1991; Mather & Harvey, 1995; Mather, 2000a, 2000b; Mather et al., 2001; Stokes, 1997; Stokes & Mather, 2003). The regional elevation differences have exerted a major control on the fluvial development of the basins, driving headward erosion and consequently drainage reorganisation of the developing river systems.

2.2.3 Transverse Drainage

Throughout the region fluvial systems have commonly developed transverse to geological structure. The main fluvial systems of the eastern part of the Sorbas basin and the Vera basin (the Rio Almanzora, Rio Antas and Rio Jauto; Fig.1.2) are developed transverse to structure (Stokes, 1997; Stokes & Mather, 2000; Stokes & Mather, 2003). All major feeder systems to the Rio Alias are transverse to structure. These include (Fig. 2.1) the proto Aguas/Feos, the Rambla de Lucainena and the Gafares (Harvey, 1987; Harvey & Wells, 1987; Mather, 1991, 1993b; Harvey et al., 1995; Mather & Harvey, 1995). The transverse course of the Aguas/Feos is argued to have been superimposed from the retreat of the Messinian-Pliocene Zorreras sea from the Sorbas basin, becoming partially antecedent with uplift of the Alhamilla/Cabreras. In contrast Stokes & Mather (2003) explain the transverse course of the Rio Almanzora (to the north of the Vera basin) by simple headwards erosion.

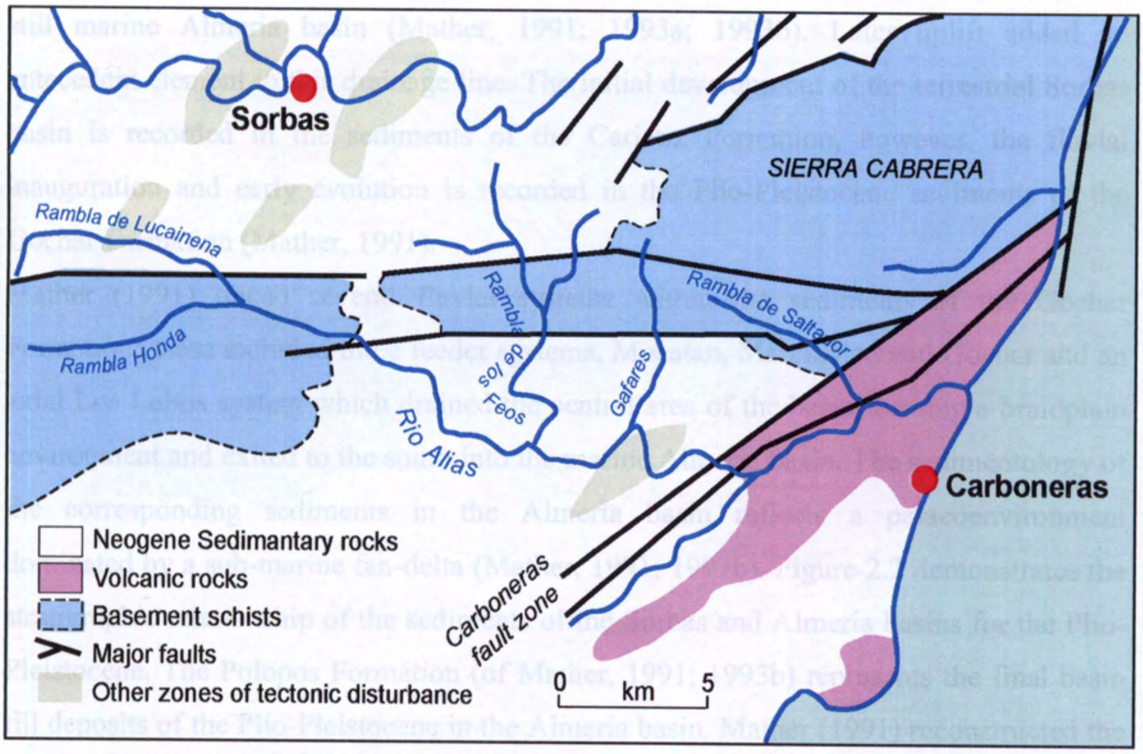


Figure 2.1. The Rio Alias and major transverse tributaries.

2.3 The Sorbas and Almeria basins: fluvial development

2.3.1 Introduction

Inter-basinal drainage is common in tectonically active basin and range settings (e.g. Robinson et al., in prep). The modern drainage network of the Rio Alias is fed by several transverse systems draining the southern margins of the Sorbas basin. Analysis of the geological (Mather, 1991) and the geomorphological (Harvey & Wells, 1987; Harvey et al., 1995; Mather and Harvey, 1995) record of the Sorbas basin however, indicates greater linkage between the Sorbas and Almeria basins throughout the evolution of the fluvial systems until c. 70ka (Candy et al., 2005).

2.3.2 Plio-Pleistocene Drainage Evolution

2.3.2.1 Sorbas Master Drainage and the Almeria Basin

Around 5 Ma the Cariatiz Sea (Mather, 1991) withdrew from the Sorbas basin and a consequent pattern of drainage formed on the emerging sea floor, the master drainage of this system passed through the structural low between the Alhamillas/Cabreras into the still marine Almeria basin (Mather, 1991; 1993a; 1993b). Later uplift added an antecedent element to this drainage line. The initial development of the terrestrial Sorbas basin is recorded in the sediments of the Cariatiz Formation, however, the fluvial inauguration and early evolution is recorded in the Plio-Pleistocene sediments of the Gochar Formation (Mather, 1991).

Mather (1991) traced several fluvial systems within the sediments of the Gochar Formation; these included three feeder systems, Mocatan, Marchalico and Gochar and an axial Los Lobos system which drained the central area of the basin forming a braidplain environment and exited to the south into the marine Almeria basin. The sedimentology of the corresponding sediments in the Almeria basin reflects a palaeoenvironment dominated by a sub-marine fan-delta (Mather, 1991; 1993b). Figure 2.2 demonstrates the stratigraphic relationship of the sediments of the Sorbas and Almeria basins for the Plio-Pleistocene. The Polopos Formation (of Mather, 1991; 1993b) represents the final basin fill deposits of the Plio-Pleistocene in the Almeria basin. Mather (1991) reconstructed the palaeoenvironmental evolution of the fluvial system using a detailed sedimentological approach analyzing alluvial architecture, sediment provenance and palaeocurrent data. The lower conglomerate unit of the Polopos Formation is composed of the initial fan-delta deposits, reflecting the progradation of the Sorbas drainage into the then marine Almeria basin. A hiatus in deposition followed and a soil developed. The upper conglomerate unit is a simple fluviatile conglomerate.

2.3.2.2 Drainage Reorganization

As drainage networks expand with time they are likely to experience reorganization in the catchment via river capture, diversion (via tilting) and beheading (Mather, 2000a). River capture has proven to be a major forcing element of drainage reorganization in areas of epeirogenic uplift in general and in this region in particular (Harvey & Wells, 1987; Harvey et al., 1995; Mather, 1991, 1993a; Mather & Harvey, 1995; Calvache & Viseras, 1997). Implications of river capture events may be varied including; re-routing of sediment supply (Clayton, 1994) base-level change (Harvey & Wells, 1987; Mather &

	Carboneras Basin	Sorbas Basin	
Polopos Formation	Upper Conglomerate Unit		Plio-Pleistocene
Polopos Formation	Ibanez Sandstone (palaeosol)	Gochar Formation	Plio-Pleistocene
Polopos Formation	Lower Conglomerate Unit		Plio-Pleistocene
	Cuevas Viejas	Cariatiz Formation	

Figure 2.2 Basin stratigraphy (adapted from Mather, 1991)

Harvey, 1995), beheading and diversion of stream networks (Bishop, 1995) and possible changes in stream biota (Waters et al., 1994; (see Mather, 2000a for more detail)).

An early major river capture event to affect the drainage of the Sorbas and Almeria basins was that of the Rambla de Lucainena (Mather, 1993a; 2000a) on the southern margin of the Sorbas basin during late Gochar times. The Rambla de Lucainena (Figure 2.1) is an aggressive subsequent stream draining west-east along the southern margin of the Sorbas basin before following a transverse course as the headwater stream of the Rio Alias. The Rambla de Lucainena cut back along an outcrop of weak Tortonian sandstones and marls, driven by the elevation differences between the two sedimentary basins, and diverted Sorbas drainage that previously flowed to the north towards the east and into the Almeria basin. The Sorbas basin thus lost c. 15% of its drainage area and suffered losses in sediment and water supply, variations in fluvial process and changing morphology of fluvial channels (Mather, 2000a).

2.3.3 The Quaternary

2.3.3.1 Aguas/Feos Master Drainage and the Rio Alias

Continued inversion of the Neogene sedimentary basins led to a situation whereby erosion came to dominate the landscape. Due to incision of the evolving drainage deposition was limited to the coast, river valleys and alluvial fans in mountain front locations (Harvey, 2001). Drainage patterns initiated in the Pliocene continued to develop their transverse courses.

The Rio Aguas (the basinal axial drainage of the Sorbas basin) draining across the structural high of the Sierra Cabrera through the valley of the Rambla de los Feos was a headstream of the Rio Alias, the main drainage system of the eastern part of the Almeria basin (Figure 2.1). The Quaternary development of this inter-basinal drainage system is recorded in a series of well developed fluvial terraces in the Sorbas basin and upper Feos valley (Harvey & Wells, 1987; Harvey et al., 1995). A combination of geomorphological mapping, sedimentological observation and clast provenance analysis of the terrace suite within the central Sorbas basin and Feos valley, established a relative chronology ascribed the nomenclature of A-E in descending stratigraphic order (Harvey & Wells, 1987; Harvey et al., 1995). The evolution of the distal reaches of the proto Aguas/Feos system, the Rio Alias, has not previously been studied.

As Figures 1.1 and 1.2 show, the current course of the upper reaches of the Rio Aguas no longer follows the proto Aguas/Feos course across the Sierras, but drains out to the east through the Vera basin to the Mediterranean. Thus a major river capture event must have occurred during the latter half of the Quaternary (Harvey & Wells, 1987; Harvey et al., 1995; Mather & Harvey, 1995; Candy et al., 2005) diverting Sorbas drainage away from the Almeria basin and the Rio Alias, to the Vera basin via the lower reaches of the Rio Aguas.

2.3.3.2 River Capture: Beheading of the Rambla de los Feos and the Rio Alias

The aggressive headwards erosion of the lower Aguas along the strike of the weak Messinian marls throughout the early Quaternary, led to the eventual beheading of the Rambla de los Feos and diversion of the Sorbas basinal drainage to the Vera basin to the east (Harvey & Wells, 1987). Consequently the distal parts of the proto Aguas/Feos system, the Rio Alias, lost >70% (Mather, 2000a) of its original drainage area (Figure

2.3). The drainage network was greatly modified and the impact upon fluvial processes, sediment/water supply and geomorphic stability across the Sorbas and Almeria basins would be both spatially and temporally persistent.

At the site of the capture event (around the village of Los Molinos, Figure 2.4) the Rio Aguas has incised by >100m since the capture reacting to a dramatic change in local base-level of the fluvial system (Harvey et al., 1995). The associated incision has cut through the more resistant lithologies to expose softer, less resistant marls that cannot support the overlying reef or gypsum complexes. This makes for a dramatic landscape of block failures and landslides throughout the steep sided gorge now developed around the capture point (Figure 2.5). Incision has propagated upstream with around 45m of incision at the village of Sorbas since the capture (Harvey et al., 1995), however, nickpoints developed further upstream have partially held up the propagation of the base-level change. In contrast, the middle Feos valley (Harvey, 2002) has experienced no incision since its beheading, with older pre-capture age river gravels buried by younger late Pleistocene and Holocene valley-side alluvial fans (Harvey & Wells, 1987; Harvey et al., 1995). The distal portions of the drainage system (the lower Feos valley and the Rio Alias) have experienced limited incision since the capture related to incision on the main stem of the Alias.

The headwaters of the Rio Alias, the Rambla de Lucainena, rise on the southern margin of the Sorbas basin and drain marginal areas of the Sorbas basin, northern and central portions of the Sierra Alhamilla and pass through the Sierras into the northern margin of the Almeria basin. The drainage area, and therefore relative stream power, was sufficient to maintain climatically driven incisional events, and therefore allowed the development of a post-capture terrace sequence along the Rio Alias. The loss of c. 70% of drainage area however, has had a substantial impact on the fluvial processes/form of the middle and lower Rio Alias (Maher et al., in press) and will be discussed later.

Initial work by Harvey & Wells (1987) based on geomorphic mapping and terrace correlation placed the timing of the Aguas/Feos river capture event between the aggradational events associated with terraces C and D (of the Rio Aguas; Harvey & Wells, 1987). Clast assemblage analysis allowed a change in sediment provenance in the

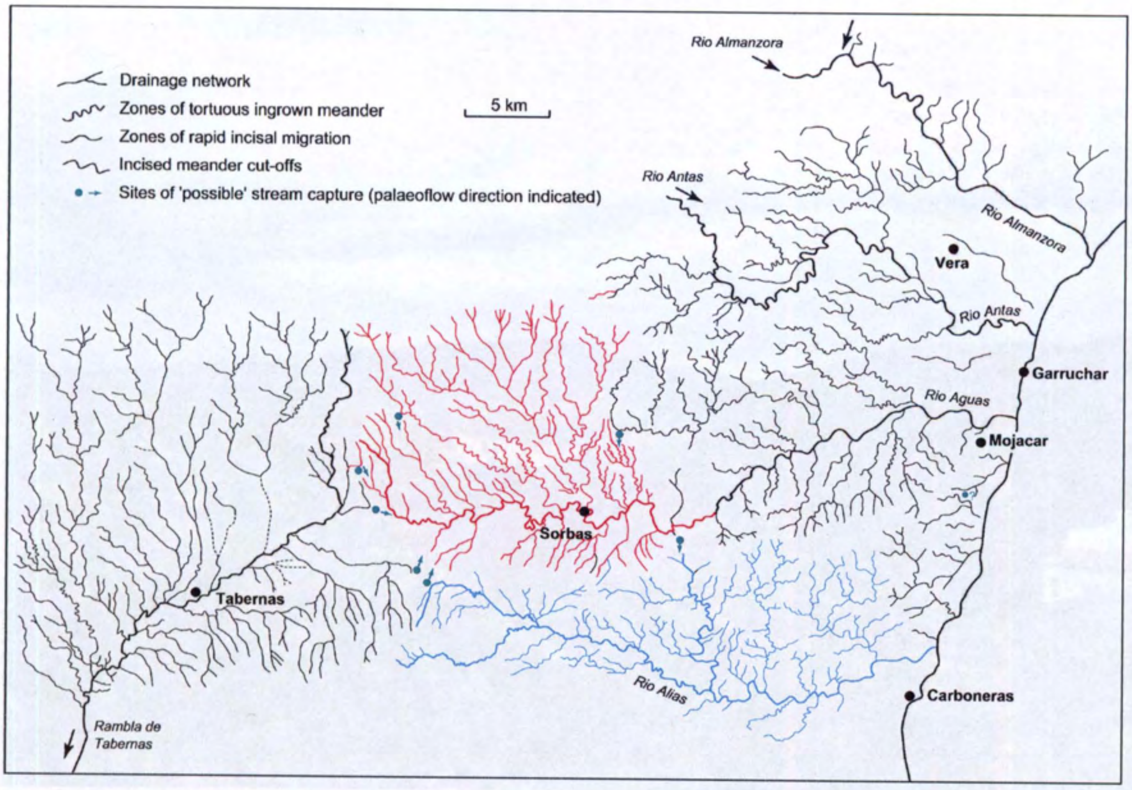


Figure 2.3 Drainage re-organization associated with the capture of the proto Aguas/Feos. Blue drainage-contemporary R. Alias. Red drainage-palaeo Aguas/Feos drainage.

sediments of the Rambla de los Feos to be identified between terraces C and D (Harvey & Wells, 1987). A drastic reduction in the amount of the diagnostic hornblende schist derived from the Sierra de los Filabres was identified between the terraces. This loss is diagnostic, as the amphibole is characteristic of the high grade metamorphics that outcrop in the northwest of the Sorbas basin only in the Sierra de Los Filabres, therefore, any loss of input of the hornblende schist relates to a loss of throughput of Sorbas drainage. Furthermore, palaeocurrent data (where available) of terraces A, B and C (pre-capture) deposits around the capture site suggest a southerly course of the Rio Aguas to the Feos valley, whilst terrace D sediments follow the easterly drainage of the Lower Aguas (Harvey & Wells, 1987).

Preliminary attempts at establishing a chronological framework were based upon soil and calcrete development on terrace surfaces (Harvey & Wells, 1987; Harvey et al., 1995). Development of the B-horizon and associated rubification (Hurst, 1977) along with the degree of pedogenic carbonate accumulation (Gile et al., 1966; Machette, 1985) often

Figure 2.4. The village to the right of the photograph is Los Molinos. The river canyon has been dissected by >110m since the capture. The last stage of through drainage is marked by terrace C, characterized by the deep red soil in the centre of the photograph. The arrow indicates the palaeo-course of the Aguas/Feos, the post-capture course of the Rio Aguas runs to the left of the photograph.

allows for the correlation of geomorphic surfaces (Bull, 1991). Moreover, Harvey & Wells (1987) suggested the timing of the capture event to be c. 100ka based upon soil and calcrete development following application and modification of Harden's soil development index (Harden et al., 1986). More recent work by Candy et al., (2005) based on U/Th dating of pedogenic calcretes in the Sorbas basin, has proposed a slightly younger date for the capture event of c.70ka. This date relates to the age of the calcrete developed on the abandoned terrace C (of Harvey & Wells, 1987) therefore the actual timing of the capture is at least 70ka (Candy et al., 2005).

2.4 Regional Controls of the Fluvial System

2.4.1 Introduction

In any fluvial system controlling factors on the behavior and evolution of a river can be characterized as internal or external to the drainage system (Schumm, 1977). External factors would be tectonics, climate, sea-level etc, and internal factors would be for example substrate geology. Throughout the region a combination of internal and external factors can be shown to drive the evolution of the fluvial system on both temporal and spatial scales.

2.4.2 Tectonics

The Sorbas and Almeria basins are within a tectonically active area. Tectonism is important in the study of long-term alluvial systems, whether it be in determining the system location (Schumm, 1977) or in its control on subsequent development (Leeder et al., 1991; Hartley, 1993). The tectonic influences on basin Formation and development

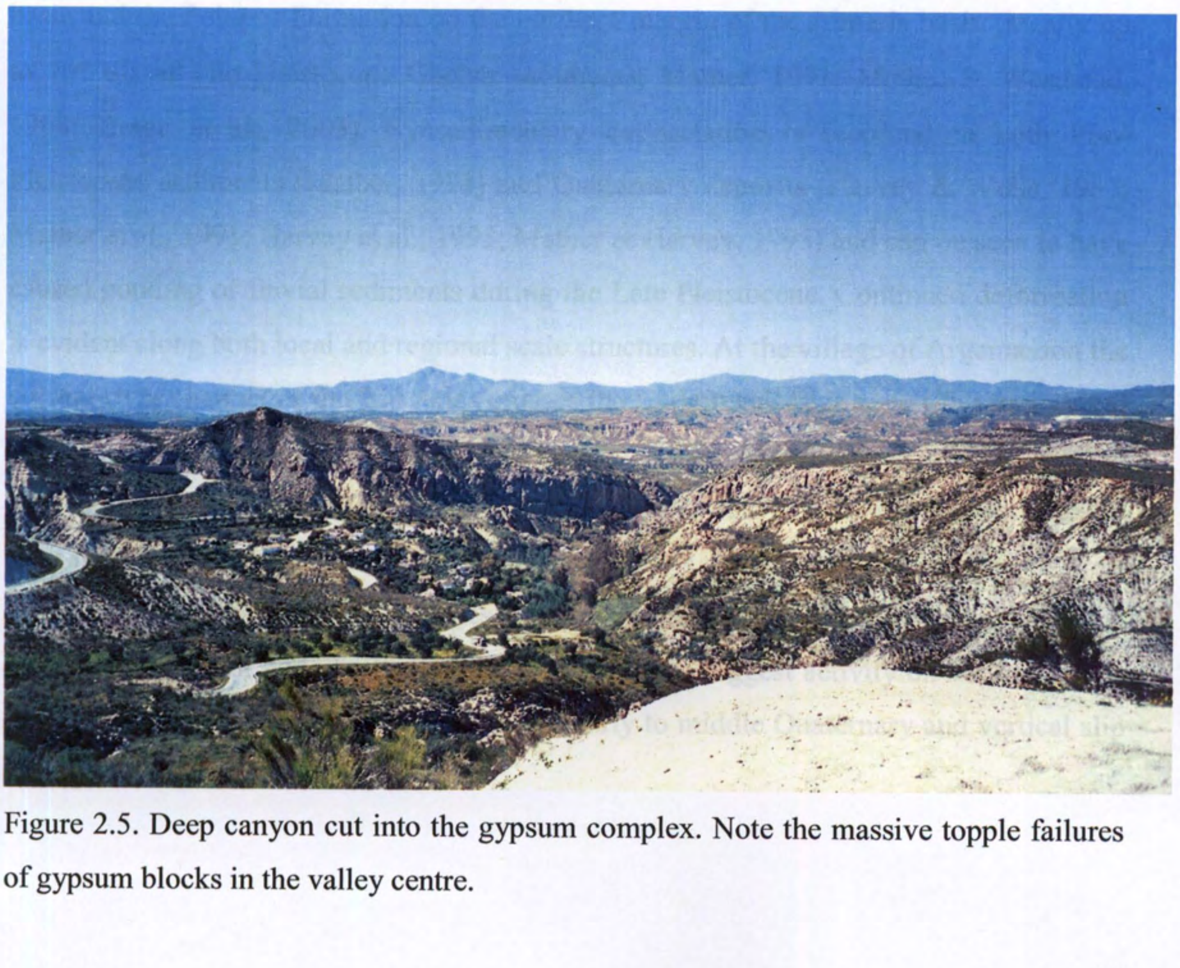


Figure 2.5. Deep canyon cut into the gypsum complex. Note the massive topple failures of gypsum blocks in the valley centre.

have already been discussed, but it is also clear that tectonic activity has continued throughout the development of this fluvial system. Regional uplift rates during the Quaternary are thought to be in excess of 160m Ma^{-1} (Mather, 1991; Mather & Westhead, 1993; Braga et al., 2003). Regional patterns of uplift created a situation within which the relative elevation of the Sorbas basin was greater than its neighbouring basins to the south and east. Braga et al. (2003) quantify amounts of uplift for the Neogene basins based upon global sea-level variations, the Almeria basin uplifted substantially less than the Sorbas basin throughout the Quaternary (c. 250m and c. 400m respectively; Figure 2.6). Thus, a gradient was created between the Sorbas and its adjacent basins to the south and east encouraging incision and headward erosion by the fluvial systems. This in turn has encouraged capture (i.e. the capture of Sorbas drainage by the aggressive subsequent Lucainena during the early Pliocene; Mather, 1991; 1993b) and the Late Pleistocene capture of the Aguas/feos system).

Continued uplift of the Sierras Alhamilla/Cabrera has caused severe deFormation within the Gochar Formation sediments (Mather, 1991) on the southern margins of the Sorbas basin and the Polopos Formation on the northern margin of the Almeria basin (locally up to 70° tilt of Plio-Pleistocene Gochar sediments; Mather, 1991; Mather & Westhead, 1993; Braga et al., 2003). Synsedimentary deFormation is recorded in both Plio-Pleistocene sediments (Mather, 1991) and Quaternary deposits (Harvey & Wells, 1987; Mather et al., 1991; Harvey et al., 1995; Mather & Harvey, 1995) and can be seen to have caused ponding of fluvial sediments during the Late Pleistocene. Continued deformation is evident along both local and regional scale structures. At the village of Argamasson the current river channel of the Rio Alias crosses the Carboneras fault zone (Figure 1.2) and Quaternary gravels are clearly deformed. An abandoned meander also makes a prominent topographic feature at the fault zone, and it is possible that this abandonment relates to fault movement. The evolution of the fluvial system is complicated throughout this area, reflecting not only upstream changes in drainage network development but also any activity of this 1km wide fault zone. Bell et al. (1997) suggest activity on the fault to be dominated by left-lateral strike-slip from the early to middle Quaternary and vertical slip through the last 100ka.

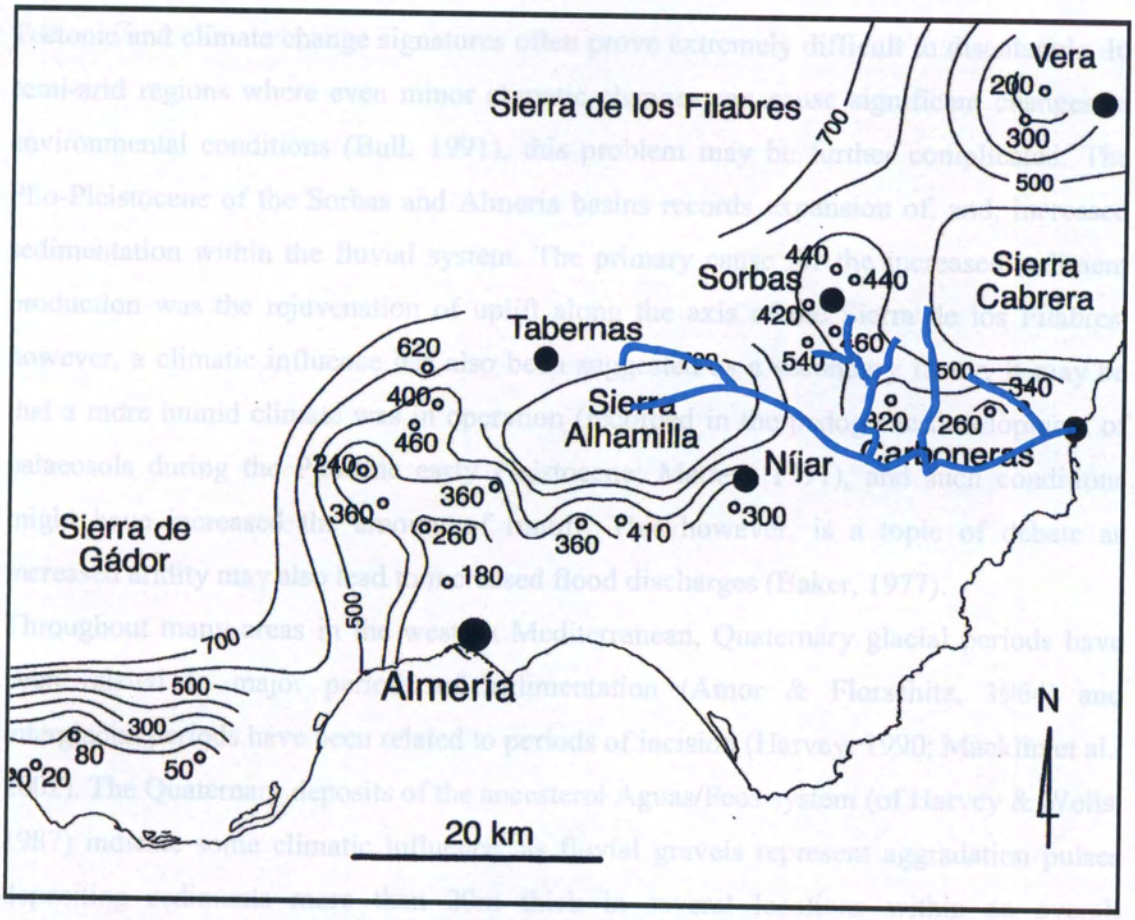


Figure 2.6 General uplift rates for the Almeria region since the Pliocene and the relative positioning of the Rio Alias. Figure adapted from Braga et al., (2003).

Tectonic activity has had a clear control on the development on the fluvial systems of the Almeria region through synsedimentary deFormation and associated deflection/ponding of the fluvial system (Mather, 1991; Mather 1993a; Mather & Harvey, 1995; Stokes, 1997). More importantly, the differential uplift of the Neogene basins drove headwards incision of transverse drainage systems and consequently led to drainage reorganisation via river capture throughout the long-term evolution of the fluvial system of the Sorbas and Almeria basins.

2.4.3 Climate

Tectonic and climate change signatures often prove extremely difficult to disentangle. In semi-arid regions where even minor climatic changes can cause significant changes in environmental conditions (Bull, 1991), this problem may be further complicated. The Plio-Pleistocene of the Sorbas and Almeria basins records expansion of, and, increased sedimentation within the fluvial system. The primary cause for the increased sediment production was the rejuvenation of uplift along the axis of the Sierra de los Filabres, however, a climatic influence has also been suggested as a secondary factor. It may be that a more humid climate was in operation (recorded in the pedogenic development of palaeosols during the Pliocene early Pleistocene; Mather, 1991), and such conditions might have increased the amount of runoff. This however, is a topic of debate as increased aridity may also lead to increased flood discharges (Baker, 1977).

Throughout many areas in the western Mediterranean, Quaternary glacial periods have been related to major periods of sedimentation (Amor & Florschitz, 1964) and interglacial periods have been related to periods of incision (Harvey, 1990; Macklin et al., 2002). The Quaternary deposits of the ancesterol Aguas/Feos system (of Harvey & Wells, 1987) indicate some climatic influence, as fluvial gravels represent aggradation pulses depositing sediments more than 20m thick in several locations within an overall dissectional regime. They result is a situation whereby tectonism creates the spatial framework along with some modification of the fluvial system, but the main aggradational/incisional terrace sequence appears to be controlled by climatic fluctuations (Macklin and Passmore, 1995; Macklin et al., 1995; Fuller et al., 1998; Kelly et al., 2000; Candy et al., 2005). Furthermore Candy et al., (2005) suggest the main phases of sediment production coincide with the cooling phases at the onset of global glacial periods.

2.4.4 Sea-level

Base-level to the distal portions of the Rio Alias is provided by the Mediterranean Sea. Quaternary sea-level oscillations across the Mediterranean have been driven by global glacial/interglacial cycles, sea-level highstands associated with interglacial periods and and periods of low sea-level corresponding to glacial phases. Throughout the last 500ka there have been several global highstand events. Across the Almeria coastal region it is those relating to Tyrhennian 1 (Oxygen Isotope Stage 7; c. 260 - 190ka) and Tyrhennain 2 (Oxygen Isotope Stage 5; c. 135 – 90ka) that are recorded in raised beach sediments (Overjaro and Zazo, 1971; Zazo et al., 1981; Goy and Zazo, 1986). During Tyrhennian 1 and 2 sea-level was several metres above the present day level, thus fore-shortening the ultimate base-level of the Rio Alias. Commonly along the Almeria coastline Tyrhennian 1 sediments are preserved at >20m above sea-level and Tyrhennian 2 at c. 5m above modern sea-level. Fluvial base-level during the intervening glacial phases would have been much lower than present day. Consequently a fluctuating marine base-level would have influenced the evolution of the distal portions of the Rio Alias controlling fluvial process and preservation in the zones immediate to and upstream of the modern coastline (for discussion see Chapter 7).

2.4.5 River Capture

River capture events have exerted a major control on the evolution of the drainage network (Harvey & Wells, 1987; Mather, 1991; Harvey et al., 1995; Mather & Harvey, 1995) diverting drainage between basins, beheading streams and dramatically altering the fluvial systems. Pirating streams such as the Rambla de Lucainena (Plio-Pleistocene Gochar Formation; Mather, 1991) and the Lower Rio Aguas (Quaternary; Harvey & Wells, 1987; Mather & Harvey, 1995) eroded headwards, driven by gradients created by differential uplift between the basins. The impact of the major river capture events has been discussed in this chapter, however, the importance of the impact of these events cannot be underestimated. Mather (2000b) emphasizes the importance of positioning of the capture point in terms of sediment re-routing. The effects of capture events are enhanced where the location of the capture point is close to mountain front locations and pirating drainages are external to the basin (Mather, 2000b), as was the case for the capture events effecting the drainage of the Sorbas and Almeria drainage systems.

Climate, tectonics, base-level and river capture interactively form major controls on the evolution of fluvial systems of the Sorbas and Almeria basins. Tectonics controls the spatial locations of the fluvial systems and drives gradient induced incision, but throughout the Quaternary it is thought that climate is the main driver of aggradational/incisional regimes (Harvey, 1987; Harvey & Wells, 1987; Harvey et al.,

1999) whilst base-level change would be an additional control at the seaward end of the system. However, the main control of drainage network evolution in southeast Spain has been river capture (Harvey & Wells, 1987; Mather & Harvey, 1995).

Chapter 3
Research Methodology

The Rio Alias in flood, April 2004

Chapter 3
Research Methodology

Chapter 3
Research Methodology

3.1 Introduction

In many studies geomorphological mapping, sedimentological analysis and analytical laboratory techniques combine to produce detailed palaeoenvironmental reconstructions (e.g. Woodward, 1990; Woodward et al., 1992; Harvey et al., 1995, 2003). Thorough analysis of the landform assemblage is vital in order to reconstruct the evolving fluvial system on both temporal and spatial scales, whilst laboratory techniques often allow inferences to be made on process-related variations of the fine sediment assemblage. In this study field mapping, sedimentology and laboratory analysis are used to establish a basis for the evolving system and can be interpreted in terms of process variations relating to possible controls by tectonics, climate, river capture and eustatic sea-level change.

3.2 Geomorphological Mapping/Sedimentological Analysis-Field Techniques

3.2.1 Introduction

The Almeria basin like the Sorbas and Tabernas basins, passed into a phase of dominant erosion with the onset of the Quaternary, and fluvial deposition became limited to river valleys and the modern coast. Along the course of the Rio Alias a suite of fluvial terraces is preserved recording the development of the fluvial system.

3.2.2 The Fluvial Terrace Assemblage

3.2.2.1 Terrace Mapping

Terrace mapping was competed using 1:25000 topographic sheets from the *Direccion General del Instituto Geografico Nacional* series, enlarged to a scale of 1:10000 for base maps. All terrace remnants were identified in the field, and as in the Sorbas basin (Harvey and Wells, 1987) 5 main groups of terraces could be defined. These were tentatively labeled A-E. Terrace surfaces were mapped on the basis of visual continuity where possible. Heights of terrace surfaces along with the height of the base of the fluvial gravel deposits (where exposed) were determined in the field. The Lower Feos valley was mapped to establish continuity with the Sorbas basin/upper Feos valley sequence, previously mapped and published by Harvey and Wells (1987) and Harvey et al., (1995).

3.2.2.2 Soil and Calcrete Development

It has been shown throughout the region (Harvey & Wells, 1987; Harvey et al., 1995, 2003; Stokes, 1997) that where soil is preserved on the terrace surface, soil and calcrete development can be used to correlate geomorphic surfaces. Soil preservation on the terraces of the Rio Alias is extremely poor with only small patchy remnants of the B horizon remaining in isolated areas. However, samples were taken for analysis of the magnetic properties (to be discussed in detail later) and soil colour was described using nomenclature from Munsell Soil Colour Charts following the procedure of Harvey & Wells (1987) and Harvey et al. (1995). Where a soil remnant was preserved the soil Redness Index was calculated following the procedures outlined in Harvey et al. (1995), soil preservation is so poor that only one sample is described for any terrace level.

The fluvial terraces of the Rio Alias are often capped by pedogenic calcretes and groundwater calcretes are commonly found within and especially at the base of the fluvial gravels. Pedogenic calcretes were recorded in terms of their stage of development (1-5) using the criteria of Gile et al (1966) and Machette (1985).

3.2.2.3 Fluvial Deposits

The height of the erosional base of the deposits associated with the fluvial terraces, where preserved, is recorded as an indicator of the previous incisional level of the river prior to aggradation of the terrace. The heights of the terrace/strath surfaces were determined from the 1:25000 topographic sheets (Table 3.1). Where the base of the terrace deposit is concealed by the modern river channel the deposit was simply recorded as such.

3.2.3 Sedimentological Analysis

Where outcrop was sufficient to determine sedimentary structures, sedimentary characteristics of the fluvial deposits were recorded. General descriptions of channel

Map District	*Topographic Sheet Number*
Lucainena de las Torres	1030-IV
Polopos	1031-III
Carboneras	1046-II
El Llano de don Antonio	1031-IV
Campohermoso	1046-I

Table 3.1 List of topographic maps used in the current study published by the *Direccion General del Instituto Geografico Nacional.*

structures, clast size, palaeocurrent indicators and deformational structures were recorded. Sedimentary sketch logs of sections were made as the depositional sequences accessible are <10m in vertical extent and as such, detailed sedimentary logging and description (using the nomenclature of Miall, 1977) was unnecessary. In zones adjacent to local tectonic control or in areas adjacent to the immediate effects of the river capture, and where outcrop permitted, analysis of the geometry of bar and channel forms was carried out. Variations in alluvial architecture can be related to changing fluvial processes and combined with particle size analyis/geomorphological analysis, were used to assess the perturbations induced by tectonic activity, river capture, base-level change or climatic fluctuation.

3.3 Sediment Provenance Analysis – Field Techniques

3.3.1 Introduction

Sediment provenance in any fluvial system consists of two components: the coarse (bedload) component and the fine (suspended) component. The processes operating on the two sediment phases can vary for any portion of the fluvial system, therefore, the lithological composition of the coarse and fine load at any given point can be very different (Woodward et al., 1992). To attempt to reconstruct sediment-source pathways throughout the evolution of this fluvial system, both the suspended load and the bedload composition were assessed.

3.3.2 Data Collection

3.3.2.1 The Coarse Component

Sediment composition of both modern channel sediments and of the terrace assemblage was determined by standard clast counting techniques used throughout the region in many studies concerning palaeoenvironmental evolution (Harvey & Wells, 1987; Mather, 1991, 2000a; Stokes, 1997; Stokes & Mather, 2003). Clasts with B (intermediate) axis >2cm where randomly sampled, and then classified according to lithological composition. Modern channel sediments and terrace sediments where also analyzed in terms of clast shape; A, B and C axis were measured and recorded along with degree of roundness. As clasts were counted they were marked with chalk as to prevent a repeat count. An average of 200 clasts was counted at each sample site.

3.3.2.2 Sediment Sampling

In order to complete laboratory analysis on the suspended load, samples were taken from both the modern river channel and terrace deposits. A 2mm sieve was taken to field locations in order to restrict the sample taken to the sand, silt and clay fraction. Samples were taken from the fluvial deposits where outcrop permitted and samples where collected from the modern channel at all major tributary junctions and at incremental positions throughout the channel system. Sediment samples were also taken at any point at which the sediment provenance signal may be expected to vary due to the input of a new lithological unit.

Sediment Size Fraction	Grain Size Assemblage
Bulk	<2mm
Coarse Sand	2000μm-500μm
Medium Sand	500μm-250μm
Fine Sand	250μm-63μm
Silt	63μm-2μm
Clay	<2μm

Table 3.2 Particle size fractions for magnetic analyses.

3.4 Sediment Provenance Analysis – Laboratory Techniques

3.4.1 Introduction

Sediment provenance studies provide important information for both geological and geomorphological investigations. Provenance variations have allowed the reconstruction of large-scale palaeogeographic variations (Haughton et al., 1991), validation of tectonic uplift and displacement models and the identification of glacial and non-glacial cycles (Woodward, 1990; Woodward et al., 1992). Within geomorphological investigations sediment provenance variations have provided valuable information regarding spatial and temporal variations in sediment supply, consequently allowing a greater understanding of catchment sediment dynamics (e.g. Yu & Oldfield, 1989).

Various procedures have been employed to determine sediment provenance variations of the fine assemblage; geochemistry (Passmore & Macklin, 1994), radionuclide concentration (Walling & Woodward, 1992; Hutchison, 1995), mineralogy (Woodward et al., 1992), SEM analysis (de Boer & Crosby, 1995) and mineral magnetics (Walling et al., 1979; Stott, 1986; Yu & Oldfield. 1989; 1993; Dearing, 1992; Caitcheon, 1993; 1998; Lees & Pethick, 1995; Walden et al., 1997; Slattery et al., 2000).

Within this study an approach combining environmental magnetism along with petrological analysis was adapted to produce a detailed reconstruction of provenance variations of the fine component of the sediment assemblage.

3.4.2 Sample Preparation

In the laboratory the samples were air dried and were separated into sand, silt and clay fractions (Table 3.2). Magnetic properties are often strongly influenced by particle size variations (Yu & Oldfield, 1993) and as such magnetic measurements were to be carried out on a particle size basis. In order to separate the particle size fractions 25g of disaggregated sediment from each sample was weighed out in a 100 cm^3 beaker and dispersed ultrasonically with the addition of 25 cm^3 of calgon and 25 cm^3 of deionized water (calgon consisting of 3.3% sodium hexametaphosphate and 0.7% sodium carbonate w/v). The sample was then wet sieved through a 63 μm brass aperture in order to separate the sands from the fines, the sands were then washed into a beaker, using distilled water, and dried at 40°C. Upon drying the sands were further sieved and separated into coarse, medium and fine fractions (Table 3.2). The sediment that had passed through the sieve was transferred to a 500 cm^3 Atterberg cylinder and filled with deionized water to 500 cm^3. The cylinder was then shaken thoroughly end over end and allowed to settle at 24.5°C, settling times were based upon Stoke's Law. After the required settling period had passed the top 20cm of the suspension was siphoned into a beaker, the process was repeated until the discharged suspension was clear. The remaining sediment component (silt) was washed into a second beaker and then both silt and clay fractions were centrifuged at 3000 rev min^{-1} on 20 minute cycles until the sediment was separated, and freeze dried overnight.

On completion of particle size fractionation, all samples were weighed and packed into 10cm^3 plastic pots in order to undergo magnetic analysis. Bulk samples were also weighed and packed for magnetic analysis and selected contemporary river channel samples were further sub-sampled in order to undergo preparation for petrological thin section analysis and SEM analysis.

3.4.3 Environmental Magnetism

3.4.3.1 Introduction

The last 30 years has witnessed the growth of the application of mineral magnetic analysis to questions of environmental processes (Thompson & Oldfield, 1986). The application provides a cheap rapid and non-destructive means to examine sediments with great sensitivity (Thompson & Oldfield, 1986; Maher, 1986; Oldfield, 1991). Since the early pioneering work of Roy Thompson and Frank Oldfield (Thompson et al., 1975) the research field has undergone great development. Both complex and subtle patterns of environmental change can be deciphered from the sedimentary record of lakes, rivers and soil profiles through the analysis of the magnetic properties of the sediment assemblage.

3.4.3.2 Measurements and Application

All substances can be defined magnetically. These magnetic properties lie within the atoms of which a substance is composed. The magnetic behaviour of an electron or atom in isolation would not produce a true description of the magnetic behaviour of a substance. However, magnetic relationships at the atomic scale do provide a major influence on the magnetic properties of substances in bulk (Smith, 1999).

The generalised magnetic behaviour of a substance can be thought of in terms of its magnetic state. A combination of magnetic measurements often allows an interpretation to be made regarding the magnetic mineral assemblage. Magnetic susceptibility measurements and remnance measurements produce subtle signals that indicate the presence of various mineral types or size. Magnetic susceptibility (χ) measures the magnetizability of a substance (Thompson & Oldfield, 1986), and can be made under different conditions to give information regarding the type, size and quantity of specific minerals in a sample (Dearing, 1999). The magnetic susceptibility of a sample is measured whilst in the presence of a small magnetic field. Remnance measurements differ from χ measurements as they examine the response of a sample to the application of a large magnetic field. The properties of the magnetic minerals are altered permanently and as such can be measured after removal from the magnetic field. Consequently, the measurements are not 'in field' per se, it is the remnance properties that are measured. Table 3.3 highlights the various remnance capabilities of the different magnetic mineral states. Not all minerals are capable of acquiring a permanent remnance, however, all minerals do respond whilst in the presence of a small magnetic field (i.e. χ measurements). As a consequence the application of both χ and remnance measurements may allow inferences to be made regarding the mineral assemblage. Furthermore, subjecting a sample to a suitable combination of applied magnetic field strengths and measuring the response can derive information regarding concentration, type and magnetic grain-size of the remnance carrying material in a sample.

Natural materials can demonstrate various styles of magnetic behaviour (Table 3.3). In nature most sediment will display a complicated mixture of magnetic minerals displaying different types of magnetic behaviour (for example see Table 3.4).

Magnetic measurements have been utilised in many different types of environmental study. Magnetic measurements are frequently used as part of a multi-proxy approach to establish patterns of environmental change. Magnetic analysis of deep-sea sediments may detect deep water current variation (Bloemendal et al., 1992), aeolian input (Robinson,

Magnetic Behaviour	Nature of Alignment	Remanence	X
Antiferromagnetism	Electron spins alternate atom by atom, thus cancelling out each generated moment.	Capable of remnance acquisition.	Weak χ.
Ferrimagnetism	Two of every three atoms line up in one direction, the third oppositely. Atoms are coupled between the different lattice layers, almost cancelling each other out.	Capable of remnance acquisition.	Strong positive χ, eg magnetite, maghemite (Fe oxides), greigite and pyrrhotite (Fe sulphides).
Canted antiferromagnetism	Electron spins are not quite antiparallel.	Stable remanence.	Moderate positive χ, eg haematite and goethite.
Paramagnetism	Electron and orbital spins have a small magnetic moment, which tends to align with the applied field.	Not capable of holding a remanence.	Weak positive χ, Fe containing minerals and salts eg biotite and olivine.
Diamagnetism	Electron and orbital spins balance out, but induced magnetic moments align in the opposite direction to the applied field.	Not capable of holding a remanence.	Weak negative χ, eg H_20, organic matter, $Si0_2$and $CaC0_3$.

Table 3.3. Magnetic behaviour and associated remanence and χ attributes.

1986) and fluvial input. Magnetic properties are inherently linked to and can be diagnostic of various soil forming processes. Maher (1986) and Dearing et al. (1996a) demonstrate how such links are distinguishable both within the individual soil profile and spatially on varying scales. Studies of loess indicate the increase of χ during interglacial periods relating to the magnetic enhancement of the palaeosols contained within the loess (e.g. Maher & Thompson, 1991). Studies encompassing mineral magnetic analysis now number in the thousands with varying degrees of success, and there are few environments within which magnetic analyses have not been applied.

Mineral	Formula	Magnetic Behaviour	Oxide/Sulphide
Magnetite	Fe_3O_4	Ferrimagnetic	Fe Oxide
Maghemite	γ-Fe_2O_3	Ferrimagnetic	Fe Oxide
Greigite	Fe_3S_4	Ferrimagnetic	Fe Sulphide
Haematite	α-Fe_2O_3	Canted Antiferromagnetic	Fe Oxide
Goethite	α-FeOOH	Canted Antiferromagnetic	Fe Oxide

Table 3.4. Common Fe-bearing minerals in sediments

3.4.3.3 Sediment Source Linkage

Mineral magnetic analysis has long been established as a means of identifying sediment source linkages (e.g. Oldfield et al., 1985; Stott, 1986; Yu & Oldfield, 1993; Oldfield & Yu, 1994; Lees, 1994; Dearing, 2000; Walden et al., 1997; Slattery et al., 2000). Sediment source ascription methodologies range from relatively simple univariate analysis and bivariate analyses (e.g. scatterplots, IRM acquisition curves) to complex multivariate analysis (including principal component analysis, cluster analysis and linear modelling-SIMPLEX). Oldfield et al (1985) identify shifting patterns in sediment source characteristics via magnetic analysis on a particle-size basis. Characterization of source materials and sediments was derived via bi-variate analysis of the magnetic signals (Oldfield et al., 1995). That study was of great importance highlighting the very real influence of particle size upon the magnetic signal and consequently, how sediment source linkages could and should be studied on a particle-size basis. The aforementioned approach produces qualitative information on the dynamics of the sediment system. However, quantitative studies are increasingly warranted and as such, mathematical unmixing models have been developed. Linear modelling relies upon the adequate statistical definition and classification of source magnetic properties. By definition, the magnetic parameters have to be linearly additive. Lees (1994) identifies major limitations to SIMPLEX modelling; 1) where the number of contributing sources is more than 4, sensible results are difficult to obtain; 2) the concentration of ferrimagnetic minerals will often mask other magnetic components (and thus some sources will be ignored whilst others are over represented); 3) sources contributing <10% are usually ignored (particularly when magnetically weak); 4) magnetic parameters are often correlated, thus Lees (1994) concluded that the best parameters to use are χ_{LF}, χ_{FD} and HIRM. Lees

(1994) work provides a strong guide for those considering the use of un-mixing models and stresses the limitations that should be addressed when considering the use of magnetic measurements in this way.

Fluvial suspended sediments, lake sediments, soils and deep-sea sediments have formed the focus of many magnetic unmixing models. Research examining the applicability of magnetic sediment source linkages to ephemeral fluvial systems is relatively rare. Caitcheon (1993; 1998) demonstrates how magnetic modelling can be utilised to assess the input of material at tributary junctions in an ephemeral stream. Tributary junction behaviour in ephemeral fluvial systems is important in terms of river dynamics and is characterised by complex relationships. It is normal in such arid/semi-arid environments (such as that of the Rio Alias) for tributaries to input more sediment than the trunk stream to the downstream system. Using magnetic parameter relationships, Caitcheon (1993) was able to quantify the relative tributary contributions to the downstream portion of the system. Further analysis of the system (Caitcheon, 1998) on a particle-size basis was able to determine the particle size range that was responsible for carrying a high percentage of the magnetic signal.

The Almeria region has previously formed the focus of a magnetics based study aiming to provide quantitative sediment source ascription for a reservoir catchment system (Yu & Oldfield, 1993). This (now silted up) reservoir is located near the village of Nijar on the southern flank of the Sierra Alhamilla (Figure 1.1). Magnetic measurements were applied to a series of possible sediment sources, the material infilling the reservoir and contemporary stream sediments. A mathematical modelling procedure was applied in order to determine the relative contributions of each source material. The results obtained allowed inferences to be made regarding the event(s) responsible for the infilling of the reservoir. The Nevado-Filabride unweathered schists (not included in their original model for contemporary channel fines) were identified as a contributor to the sediments that infill the reservoir, as the model offers good results when they are included as a possible sediment source. The results also suggest that it was high magnitude low frequency events that were responsible for the filling up of the reservoir.

Perhaps a more informative study was that of Harvey et al. (2003) addressing questions of sediment provenance of alluvial fan and lake sediments via analysis of inter-parametric ratios, bi-variate plots and simple through-sequence variations in mineral concentration and grain size parameters. Environmental interpretations were consequently made regarding phases of climatically forced hillslope erosion.

Such studies highlight the applicability of mineral magnetic studies to questions of sediment provenance in arid-zone, ephemeral fluvial systems. Increased understanding of sediment movement in such systems will be of great value, as downstream connectivity of sediment is poorly understood. The nature of deposition in such sedimentary environments is such that processes of diagenetic/authigenic alteration are minimal, and consequently should not cause any significant alteration of the magnetic signal.

Source components within the Almeria basin are likely to be dominated by sandstones, marls, gypsum, calc-alkaline volcanics, metamorphic basement and re-worked Quaternary fluvial deposits. Consequently, analysis of the magnetic assemblage is more likely to produce realistic results when evaluated on a sub-basin scale, therefore, reducing possible source components.

3.4.2.4 Pedogenic Analysis

The Almeria region has also formed a focal point of previous magnetic studies relating to soil development on Quaternary alluvial fans (Harvey et al., 1999; 2003) and river terrace surfaces (Harvey et al., 1995). The development of soil profiles on the various remnant terraces was examined in great detail by Harvey et al. (1995). One element of this analysis was the application of mineral magnetic measurements to the soil profiles in order to attempt to derive age-dependant properties. No apparent relationship between the primary magnetic data (using the common magnetic parameters and ratios) and soil age (as expressed by the Bt horizons) could be inferred (Harvey et al., 1995). Harvey et al., (1999) however, do record an increase in $\chi_{FD\%}$ with increasingly older alluvial fan surfaces suggesting the mineral magnetic technique can detect age dependant relationships (Harvey et al., 2003). Encouragingly, current work (Hannam and Foster, 2005) on the soils of the terrace sequence of the Rio Aguas further informs a trend of increasing χ_{FD} values on increasingly older surfaces.

Studies in other dryland areas such as those of White & Walden (1994; 1997), have produced positive results suggesting the build up of iron oxides in soils over time on alluvial fans in the arid environment of the Tunisian Southern Atlas. Magnetic measurements also proved to be more sensitive than Munsell soil colour analysis for estimating the concentration of Fe oxides (White & Walden, 1994). The results obtained suggest that mineral magnetic analysis could be used to establish an ordinal chronology on surfaces characterised by well-developed soil profiles. More recent work (Pope, 2000) supports the notion of the application of magnetic measurements to the analysis of arid zone soils.

As has already been mentioned the soil profile preservation within the Almeria basin is extremely poor, and consequently detailed examination of the magnetic properties of soils is not possible. However, where remnant patches of the B horizon occurred, magnetic analysis was performed, enabling correlation and continuity of terrace levels between the Sorbas and Almeria basins to be assessed.

3.4.3 Mineralogy

3.4.3.1 Petrological Analysis

Mineral magnetic analysis provides detailed information regarding the ***types*** of minerals contained within a sample; however, it does not render precise information regarding specific minerals. Therefore further analysis is required to establish the actual minerals present in a sample.

Thin sections were made on contemporary channel sediments (<2mm fraction) from 16 locations (Figure 3.1). Slides were analysed to identify the mineral/grain assemblage, general observations were made regarding the minerals present and detailed counts were made on the lithic grain assemblage (J.D. Marshall, Pers. Comm.). Counts were made on point counters used for standard thin section analysis and 200 counts were made on each slide following the guidelines of the nomograph for determination of counting error taken from Folk (1983).

3.4.3.2 Mineral Analysis

The quality of the slides was such that the identification of individual minerals was possible, but limited in terms of collecting quantitative data for each sample, consequently more reliable data could be gained from analyzing the assemblage in terms of lithic fragments rather than individual minerals. In order to determine what minerals were present sub-samples were taken from the key tributary junctions (Figure 3.1) and prepared for analysis under the Scanning Electron Microscope (SEM). Samples were carbon coated and examined on a Phillips XL30 SEM using 15-20 Kv accelerating voltage. Energy Dispersive X-Ray Anlaysis (EDAX) was performed using the Link ISIS 300 Series system to establish mineral composition following Welton (1984). The slides were examined, 150 grain counts were made, and the mineral assemblages and associations were noted.

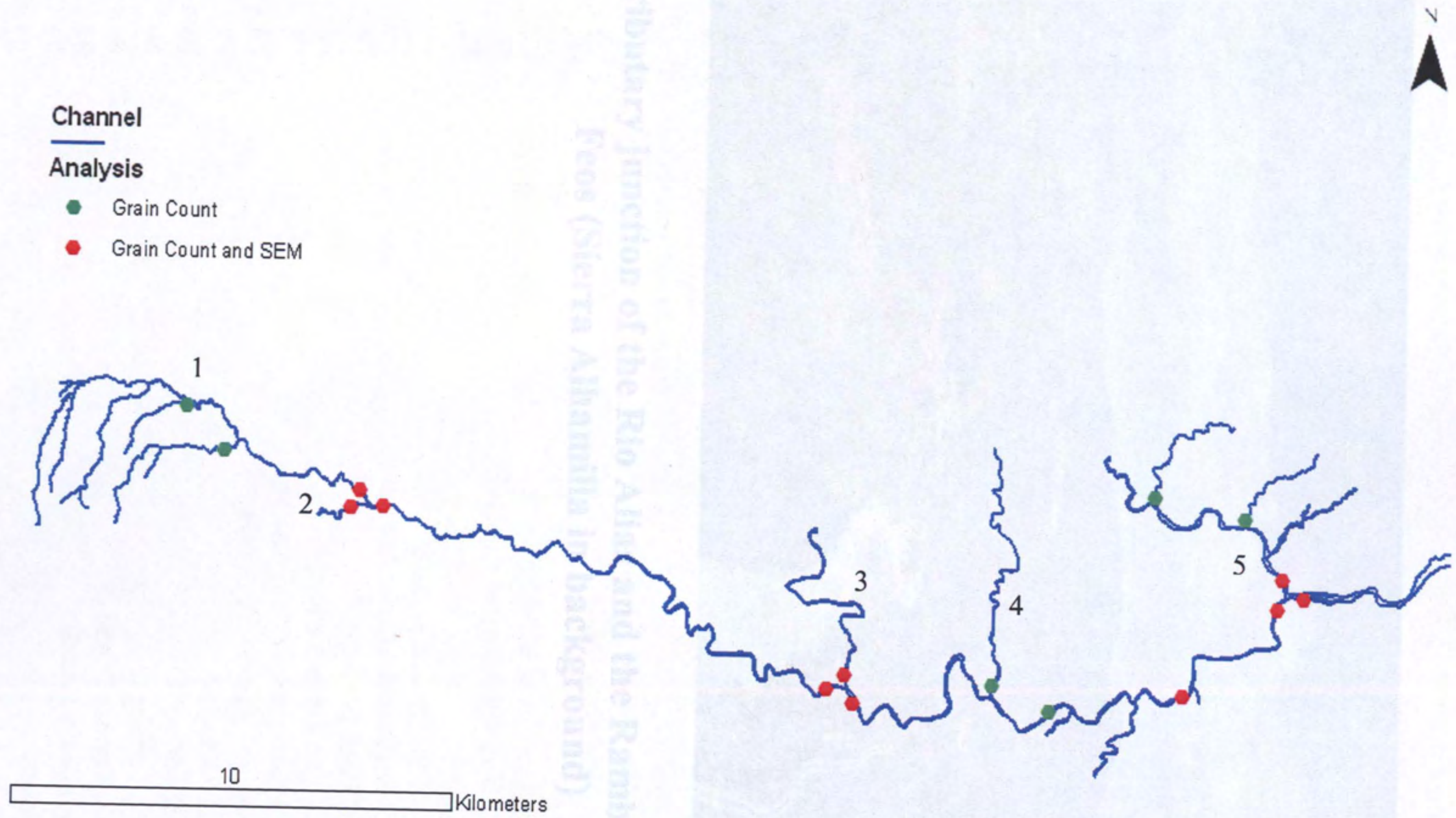


Figure 3.1. Location of SEM/petrological analysis on contemporary fine (<2mm) channel sediments. 1- Lucainena headwaters. 2- Rambla Honda. 3- Rambla de los Feos. 4- Gafares. 5- Rambla Saltador.

Chapter 4
Establishing The Sequence

Tributary junction of the Rio Alias and the Rambla de los Feos (Sierra Alhamilla in background)

Chapter 4
Establishing The Sequence

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Establishing The Sequence

4.1 Introduction

The fluvial terraces preserved throughout the drainage basin of the Rio Alias have been mapped and ascribed a relative terrace stage A-E from oldest to youngest. Terraces A-D are spatially persistent across the basin whilst terrace E remnants are patchy. Locally terraces A and C have been sub-divided. Figure 4.1.1 shows the terrace assemblage for the trunk stream and the major tributaries of the Rio Alias and Figure 4.1.2 the long-profile for the main river system. As has been previously described the overall positioning of the fluvial system has been controlled by tectonics, whereas climate has driven the aggradational/incisional regime on a regional scale. When examining the evolution of the Rio Alias however, it has to be considered in terms of a series of evolving sub-reaches themselves positioned due to the location of regional tectonic structures and the modern coastline. There are four sub-reaches: 1) the Lucainena, 2) the Polopos, 3) the Argamason, and 4) the El Saltador sub-reach.

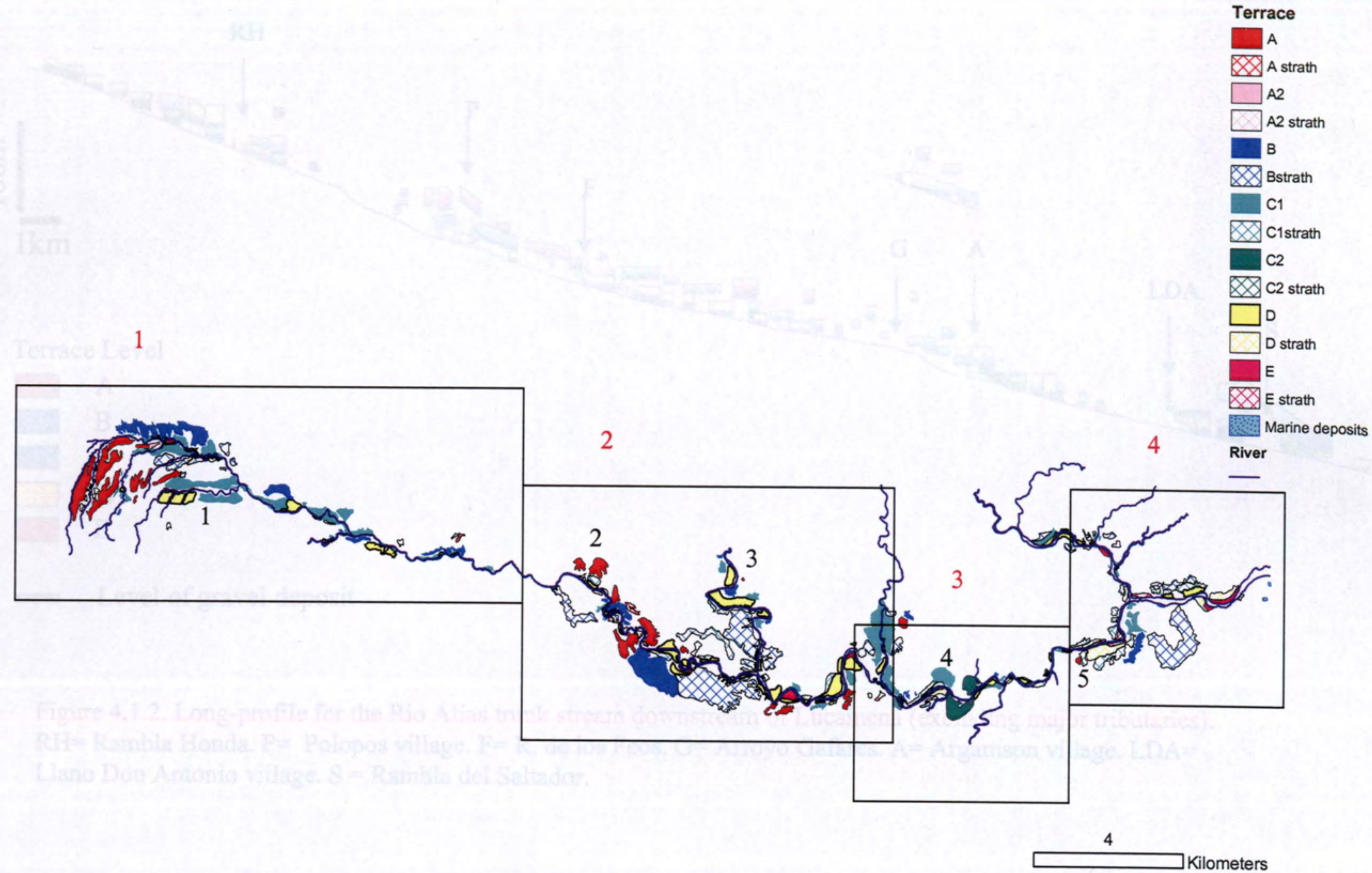


Figure 4.1.1. Terrace map for the Rio Alias. 1) Lucainena. 2) Polopos. 3) Rambla de los Feos. 4) Argamasson. 5) Llano don Antonio. Boxes indicate the position of the 4 sub-reachs labelled in red: 1) Lucainena. 2) Polopos. 3) Argamason. 4) El Saltador.

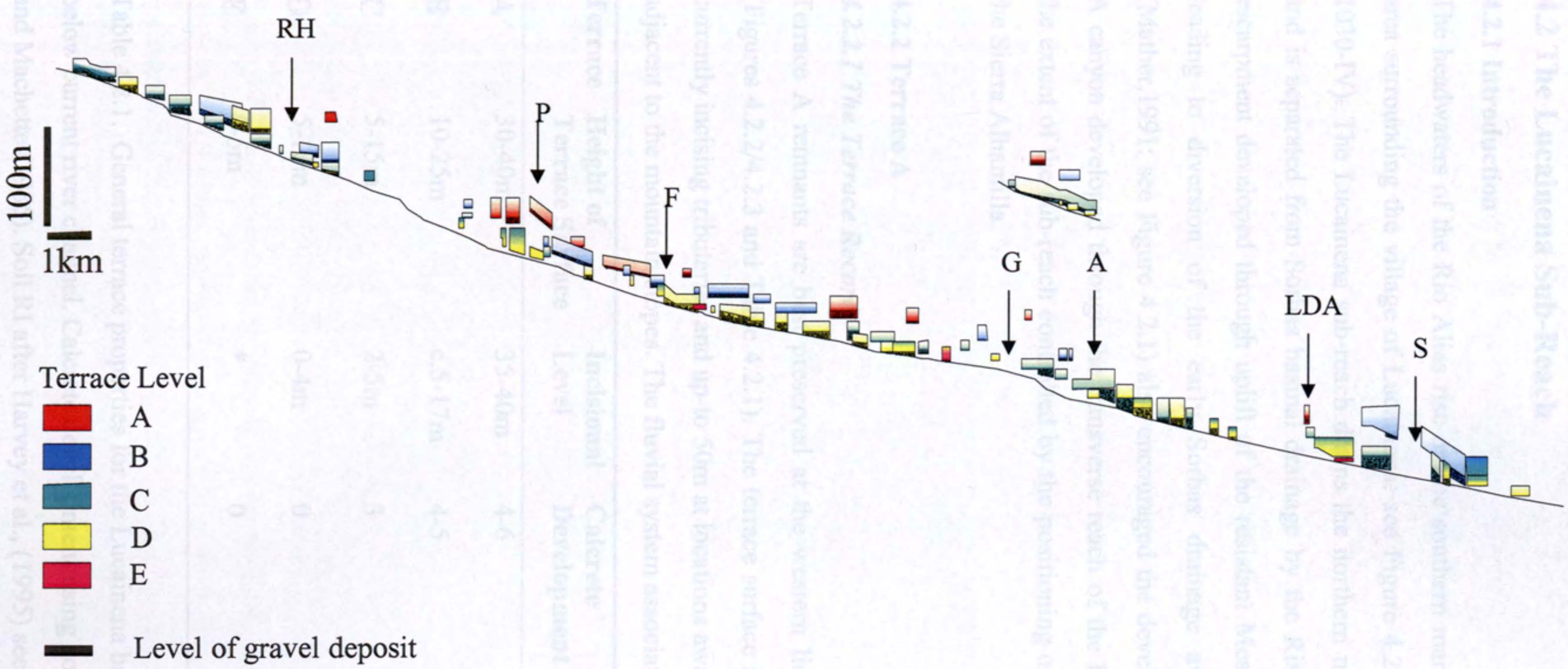


Figure 4.1.2. Long-profile for the Rio Alias trunk stream downstream of Lucainena (excluding major tributaries). RH= Rambla Honda. P= Polopos village. F= R. de los Feos. G= Arroyo Gafares. A= Argamson village. LDA= Llano Don Antonio village. S = Rambla del Saltador.

4.2 The Lucainena Sub-Reach

4.2.1 Introduction

The headwaters of the Rio Alias rise on the southern margin of the Sorbas basin in the area surrounding the village of Lucainena: see Figure 4.2.2 (GR 5712 4100; Sheet No. 1030-IV). The Lucainena sub-reach drains the northern margin of the Sierra Alhamilla and is separated from Sorbas basinal drainage by the Risco de Sanchez, the limestone escarpment developed through uplift of the resistant Messinian bedrock. River capture leading to diversion of the early Sorbas drainage away from the Sorbas basin (Mather,1991: see Figure 4.2.1) also encouraged the development of the resistant ridge. A canyon developed through the transverse reach of the Rambla de Lucainena delimits the extent of the sub-reach controlled by the positioning of the major bounding faults of the Sierra Alhamilla.

4.2.2 Terrace A

4.2.2.1 The Terrace Record

Terrace A remnants are best preserved at the western limits of the Lucainena system (Figures 4.2.2/4.2.3 and Table 4.2.1). The terrace surface is between 30-40 m above the currently incising tributaries and up-to 50m at locations away from the incising tributaries adjacent to the mountain slopes. The fluvial system associated with terrace stage A is

Terrace	Height of Terrace Surface	Incisional Level	Calcrete Development	Soil RI	Cementation/ Induration
A	30-40m	35-40m	4-6	11.25	Cemented and indurated
B	10-25m	c.5-17m	4-5	N/A	Cemented and indurated
C	5-15m	2-5m	3	7.5	Cemented some induration
D	5-10m	0-4m	0	0.6	Loose sediment
E	0-5m	*	0	N/A	Loose sediment

Table 4.2.1. General terrace properties for the Lucainena basin, * denotes incisional level below current river channel. Calcrete development using notation of Gile et al., (1966) and Machette (1985). Soil RI after Harvey et al., (1995) see section 3.2.2 for explanation.

incised to c. 35-40 m above the level of the current fluvial system and is characterised by a thin (generally <2m) veneer of fluvial gravels. The surfaces dip into the basin from the mountain front boundary in a north and north-west direction. Due to a lack of depositional material it cannot be ascertained whether the tilt of the surface is due to initial development of the fluvial system on a tilted topographic surface (a pediment), or, whether it is due to syn/post-depositional tilting of Terrace A. Only one further remnant of terrace A is preserved at the distal portion of the Lucainena sub-reach and it is a strath surface preserved in isolation in the canyon reach. Re-organisation of the drainage network following terrace A times is postulated for the boundary of the Sorbas/Almeria drainage and will be discussed in section 4.2.6.

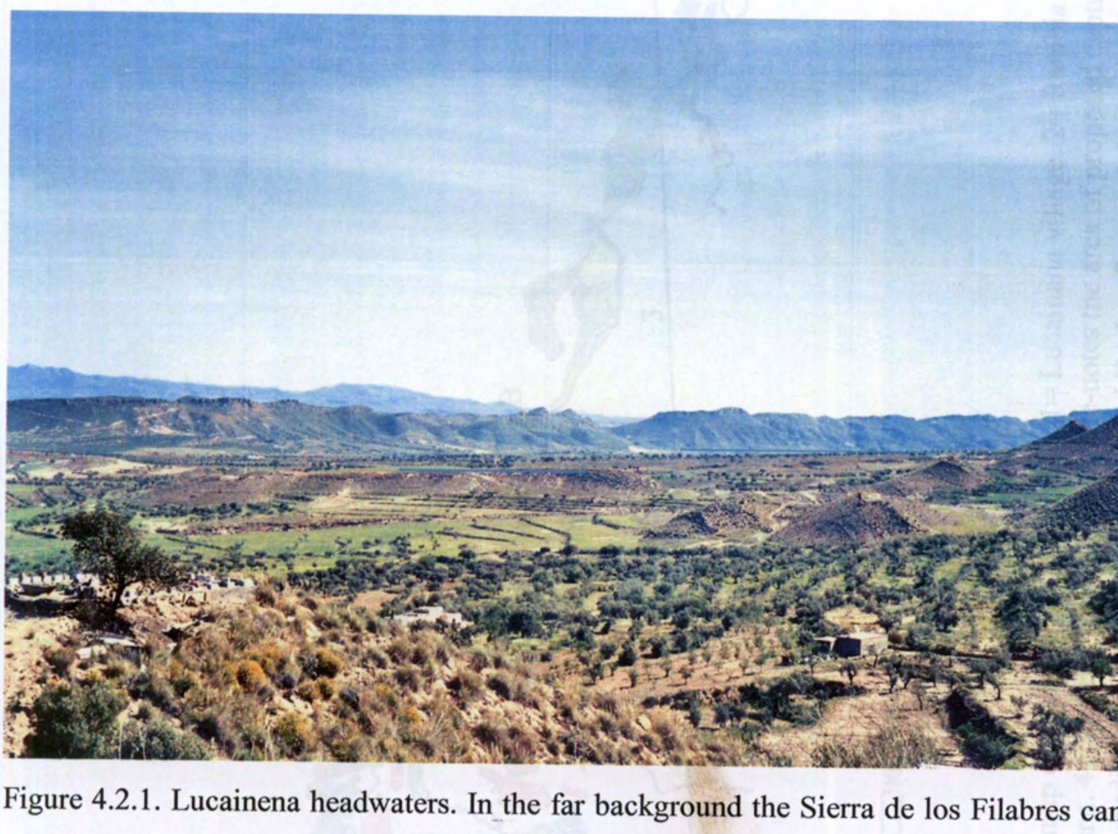


Figure 4.2.1. Lucainena headwaters. In the far background the Sierra de los Filabres can be seen and in the middle distance the Riscos de Sanchez separates the Lucainena drainage from the Sorbas basin. Terrace A, marked by the blue dashed line, can be distinguished in the middle ground associated with a thin surface gravel veneer.

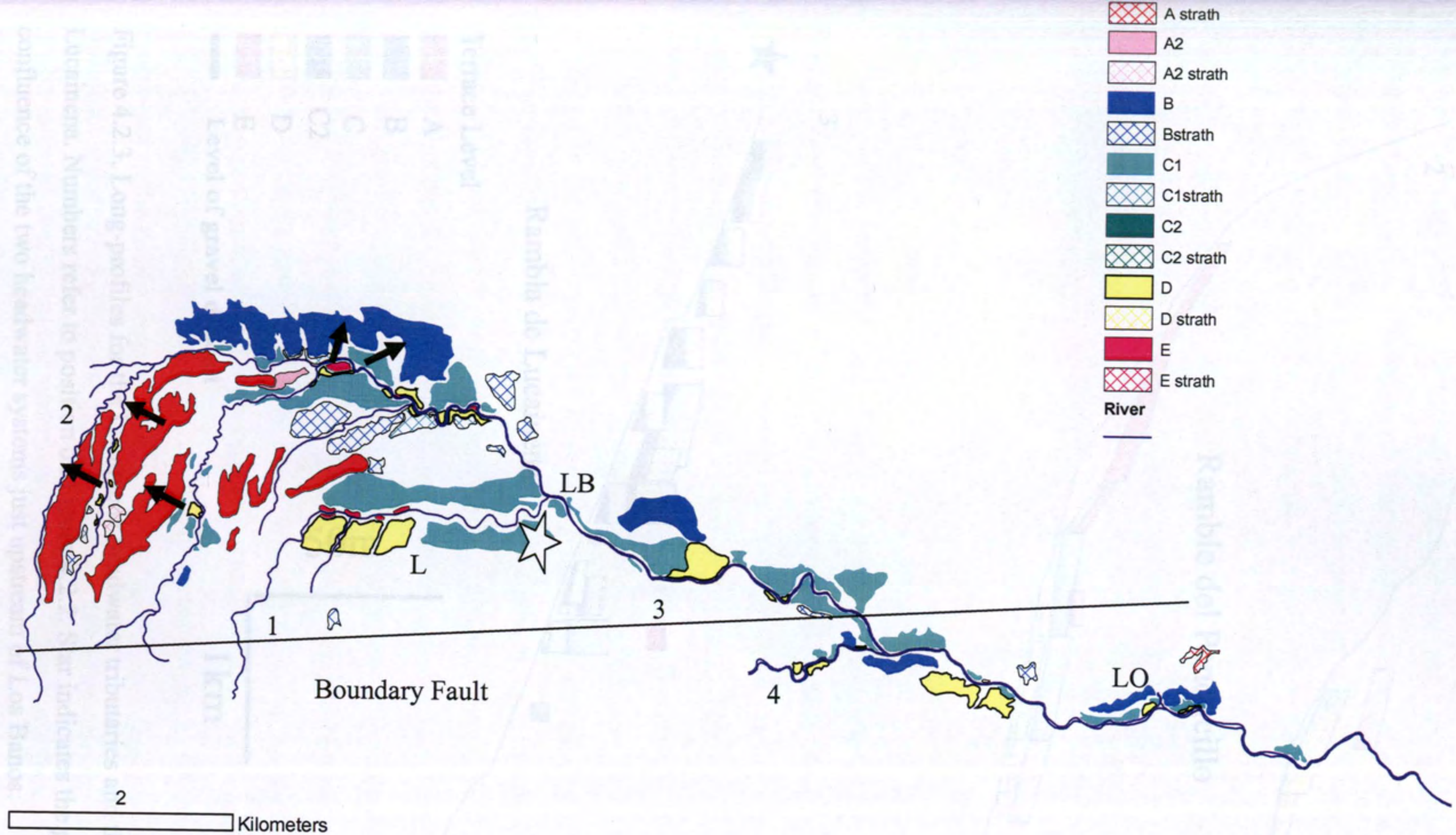


Figure 4.2.2 . Terrace map of the Lucainena sub-reach. 1= Lucainana village. 2= Rambla del Penoncillo. 3= Rambla de Lucainena. 4= Rambla Honda. The star de-notes the area of proposed capture. Arrows indicate slope direction of the terrace/pediments. L= Lucainena village. LB= Los Banos. LO= Los Olivillos

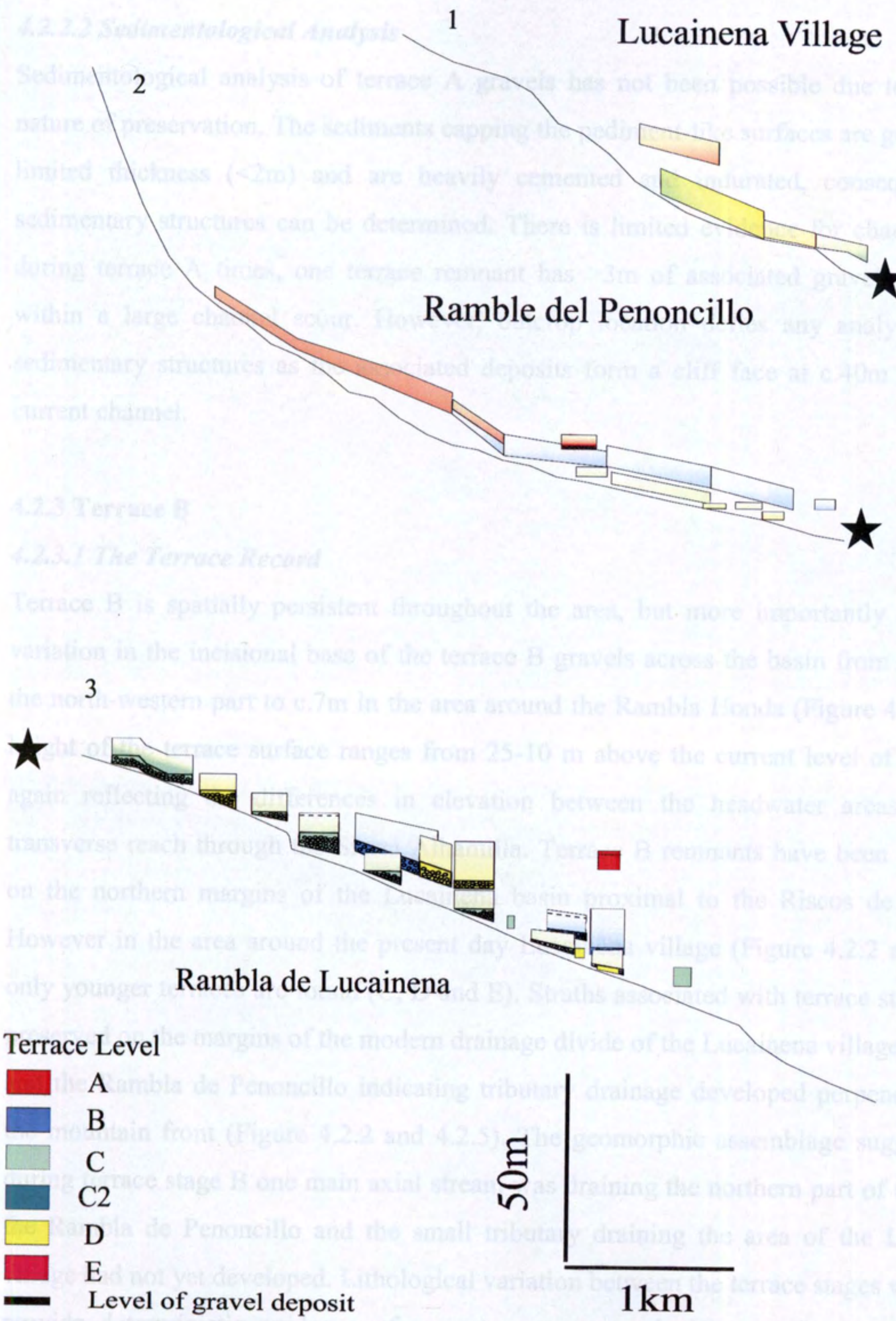


Figure 4.2.3. Long-profiles for the Lucainena headwater tributaries and the Rambla de Lucainena. Numbers refer to position on Figure 4.2.2. Star indicates the position of the confluence of the two headwater systems just upstream of Los Banos.

4.2.2.2 Sedimentological Analysis

Sedimentological analysis of terrace A gravels has not been possible due to the poor nature of preservation. The sediments capping the pediment-like surfaces are generally of limited thickness (<2m) and are heavily cemented and indurated, consequently no sedimentary structures can be determined. There is limited evidence for channelisation during terrace A times, one terrace remnant has >3m of associated gravels contained within a large channel scour. However, outcrop location defies any analysis of the sedimentary structures as the associated deposits form a cliff face at c.40m above the current channel.

4.2.3 Terrace B

4.2.3.1 The Terrace Record

Terrace B is spatially persistent throughout the area, but more importantly there is a variation in the incisional base of the terrace B gravels across the basin from c. 18m in the north-western part to c.7m in the area around the Rambla Honda (Figure 4.2.3). The height of the terrace surface ranges from 25-10 m above the current level of the river, again reflecting the differences in elevation between the headwater areas and the transverse reach through the Sierra Alhamilla. Terrace B remnants have been preserved on the northern margins of the Lucainena basin proximal to the Riscos de Sanchez. However in the area around the present day Lucainena village (Figure 4.2.2 and 4.2.4) only younger terraces are found (C, D and E). Straths associated with terrace stage B are preserved on the margins of the modern drainage divide of the Lucainena village tributary and the Rambla de Penoncillo indicating tributary drainage developed perpendicular to the mountain front (Figure 4.2.2 and 4.2.5). The geomorphic assemblage suggests that during terrace stage B one main axial stream was draining the northern part of the basin, the Rambla de Penoncillo and the small tributary draining the area of the Lucainena village had not yet developed. Lithological variation between the terrace stages would not provide deterministic evidence of a capture event as both streams provide similar lithologies to the fluvial system, however, some inferences regarding provenance can be made (to be discussed later). Sedimentological variation between the terraces may reflect process-related changes in the system and could be related to a loss of drainage area (to be discussed in detail in section 4.2.3.2).

Figure 4.2.4. Lucainena village headwater stream-terraces C-E and palaeo-channel B indicated. View to the east.

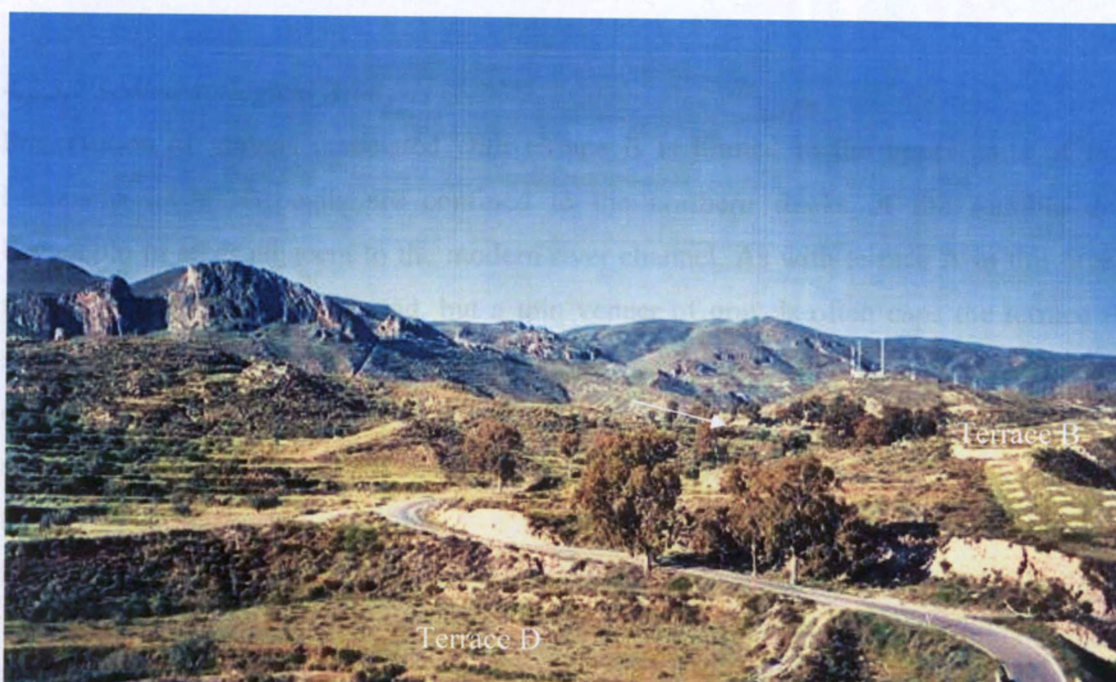


Figure 4.2.5. B Palaeo-channel (arrow) and terraces B and D in foreground.

Downstream of the village of Lucainena the Rambla de Lucainena becomes a single thread system and the occurrence of terrace B diminishes with only a palaeo-valley preserved (Figure 4.2.2) and a small outcrop of sediments with no associated terrace. As the fluvial system crosses the northern boundary fault and moves into the Sierra Alhamilla there is a significant decrease in both the aggradational and incisional level of terrace B (Figure 4.2.3). At the tributary junction of the Rambla Honda the incisional level of the base of terrace B deposits is c. 5-8m above the modern channel and the aggradational surface is 10-15m above the channel (Figure 4.2.6). The apparent decrease in the level of terrace B suggests uplift along the axis of the Sierra Alhamilla effectively causing a decrease in the local base-level and consequently merging of the terrace levels. Across this transverse portion of the system, valley width is limited due to the resistant nature of the bedrock and the uplifting Sierras, a canyon is developed throughout most of the area with terrace remnants preserved only at the Honda/Lucainena junction and Los Olivillos (Figure 4.2.1). At Los Olivillos the incisional level of terrace B gravels is c. 10m, and the aggradational level is between 20 and 15 m above the modern channel (Figure 4.2.3).

4.2.3.2 Sedimentological Analysis

Preservation of gravels associated with terrace B is limited in the upper parts of the Lucainena basin. Deposits are confined to the northern flanks of the Rambla del Penoncillo in areas adjacent to the modern river channel. As with terrace A in this area, no significant deposits are found, but a thin veneer of gravels often caps the terrace B surface: around 1m of cemented coarse gravels with average B axis of 3cm and no discernable sedimentological structures (Figure 4.2.7). Channelised deposits or a sufficient amount of deposit to allow sedimentological analysis have not been located in this portion of the basin.

Fluvial gravels are preserved around the Rambla Honda junction and at Los Olivillos. The deposits shown in Figure 4.2.7 are c.8m thick downstream of the Rambla Honda junction. Detailed sedimentological analysis could not be completed due to inaccessibility of the outcrop, however, the sediments are coarse with channel structures preserved. Downstream of Los Olivillos 3m of terrace B grravels are preserved overlying an erosive unconformity into local schists (Figure 4.2.8). The sequence is characterised by a series

Figure 4.2.6. Terrace B Rambla Honda/Rambla de Lucainena tributary junction.

Figure 4.2.7. Terrace assemblage on Rambla del Penoncillo, the area affected by the capture of drainage to the Lucainena village stream. Gravels associated with terrace B are up to 2m thick (see capping sediments on terrace B surface).

Figure 4.2.8. Sketch log of terrace B deposits. Thick black lines highlight erosional surfaces/channels, yellow lines indicates fore-sets.

Figure 4.2.9. Well developed soil profile and pedogenic calcrete on terrace C. T-shirt for scale is c.70cm.

of stacked channels c.1m deep with associated lateral accretion surfaces. The valley width at terrace B times was much broader than that of today, and as such could have supported a meandering channel belt suggested by the architecture of the small outcrop of sediments. The valley sides where probably characterised by hillslope fed alluvial fans or debris mantled pediments as suggested by the geomorphic assemblage. Terrace B has since been covered in places by younger colluvial slope deposits and within the canyon by valley-side alluvial fans associated with terrace stage D.

4.2.4 Terrace C

4.2.4.1 The Terrace Record

Terrace C is the most spatially persistent of all the terrace stages in the Lucainena sub-reach and has good preservation of associated sedimentary sequences whilst outcrops are generally accessible and easily logged. In the steep headwater areas as with most of the terrace stages, the terrace remnants are associated with pediment or strath development and deposits are preserved only away from the mountain front. Terrace C is the youngest stage to be associated with significant rubification of remnant soil pockets (Figure 4.2.9), preserved calcrete development and possible cementation of the deposit. The aggradational height of terrace C is generally c. 10 m above the modern day channel, but can be as low as 5m in the transverse reach of the Rambla de Lucainena (Figure 4.2.3). The incisional level of the gravels is generally c.3-5m above the modern drainage but again throughout the transverse reach the level decreases to c. 2m and c. 100m downstream of Los Banos (Figure 4.2.2) the level is between 1-2 m.

In the western portion of the basin terrace C has spatially consistent characteristics in terms of aggradational/incisional levels throughout the drainage of both the Rambla del Penoncillo and the Lucainena village stream. The headwater systems meet in the area around Los Banos and c.100m downstream from this location there is a significant drop in the incisional level of the gravels (Figure 4.2.3) to around 1m above the modern channel (Figure 4.2.10). One possibility for this local variation in incisional level could be the preservation of both mid-channel and valley side remnants of the C stage fluvial system at this location. However, due to the gradual rise in the incisional level downstream of Los Banos, and a sequence through C age deposits that reveals a palaeochannel and valley sequence with the valley side deposits c. 10m above the modern

Figure 4.2.10. Terrace C deposits: the incisional level of the unit is below the level of the modern channel. The base of the gravels is not observed.

channel (Figure 4.2.11) upstream of the Rambla Honda junction, a tectonic lowering of base-level by local-faulting is proposed. There are no obvious expressions of faulting or syn-sedimentary deformation within the Quaternary sedimentary units; however, there is an anomalous unit of bedrock situated immediately behind the lowest incisional level of terrace C. Immediately behind the section an anomalous unit of bedrock displays different lithological characteristics to the surrounding bedrock and may be deformed along a fault. Furthermore, the orientation of the proposed fault line follows that of a structural lineament: the Infierno Marchalico Lineament of Mather and Westhead (1993) which has been active during the Plio-Quaternary. The fault activity would have occurred between the aggradational events associated with terraces B and C altering local base-level around the Los Banos area. The timing of the fault movement would also coincide with the proposed development of the Lucainena village tributary system (see section 4.2.6.3). Terrace C occupies a broad valley position around the village of Lucainena dominating the terrace assemblage, the incisional level is c.2-3m above the modern channel but is unobservable at the junction with the Rambla del Penoncillo due to anthropogenic alteration of the modern channel.

Terrace C is spatially persistent throughout the basin and remnants are preserved throughout the eastern portion of the basin, downstream as far as the canyon reach downstream of Los Olivillos. In the transverse reach of the Rambla de Lucainena around the junction with the Rambla Honda, terrace C deposits are c.1-2m above the modern channel. As with terrace B deposits there is a decrease in the level of the incisional cut of terrace C as the river crosses the northern boundary fault, suggesting limited uplift of the Sierra Alhamilla, though to a lesser extent than since terrace B times.

4.2.4.2 Sedimentological Analysis

Gravels of terrace C are well preserved throughout the basin. Deposits on the Rambla del Penoncillo (around the area that would have been affected by a loss in drainage from the Lucainena village area) are somewhat different to those preserved elsewhere in the basin as they are predominantly fine grained and reflect a fluvial system with an apparent decrease in stream power (Figure 4.2.12). This is in contrast to the remnant deposits associated with terrace stage B. The fluvial deposits are dominated by massive sandy units with intercalations of gravel sheets, and exhibit limited wide and shallow channel development (width <5m and depth <1m) with gravel to cobble fills and associated lateral aggradational surfaces. The coarse component of the channel fill is likely to reflect extremely localised erosion of the Tortonian sandstone bedrock, and the collapse of channel margin material. The dominance of fine-grained material in the terrace C associated deposits at this location may be due to two factors; the proposed loss of drainage to the newly developed Lucainena village tributary system hence a decrease in relative stream power and transport capabilities, or, new tributary erosion into Tortonian bedrock leading to fluvial sediments dominantly sourced from fine grained sand and marl lithologies. Given that the general nature of the remaining deposits throughout the basin is of a coarse conglomeratic facies, it seems unlikely that input of newly eroded fine grade material alone could create such a contrast in fluvial architecture. Furthermore sediments of terrace D in this area have a significantly increased proportion of gravel sized material within the deposits suggesting that liberation of gravel sized material to this portion of the system is possible.

Figure 4.2.11a. Sketch log of terrace C on the northern margin of the Sierra Alhamilla. Note the original valley side of the channel belt is preserved. Heavy black line indicates incisional base of terrace deposits. Intermediate line represents erosional scours/channel structures and fine lines indicate foreset development. White dashed lines indicate fine hillslope-derived sediment.

Figure 4.2.11b. Sketch log of the key features of terrace C on the opposite side of the valley to that shown above. No original valley wall preserved. Sketch highlights the major incisional level of the terrace deposits, erosional horizons and foreset development (as above).

Around the village of Lucainena terrace C deposits are preserved, though in most places they have been covered by younger deposits. Limited sequences (terrace C on Figure 4.2.2) suggest a meandering gravel bed system with channel migration away from the mountain front across the valley. Downstream of the location where the triumvirate of headwater streams merge as the single Rambla de Lucainena, terrace C deposits are widespread (Figure 4.2.2) and can be traced downstream to the canyon reach. Downstream of Los Banos there is a significant spatially persistent sedimentary unit, characterised by a sequence of stacked channels, with coarse gravel-cobble fills (Figure 4.2.10). The overall sequence through this reach is suggestive of a coarse, bedload-dominated braided system. Individual channel geometries range between 0.5 and 1m depth and 2-3m width (Figure 4.2.10). Lateral accretion surfaces associated with point bar migration are common within the deposits reflecting the migrating nature of the channel belt.

As the Rambla de Lucainena crosses the mountain front at the junction with the Rambla Honda, terrace C deposits denote the development of a very extensive indurated ground water calcrete (Figure 4.2.13). The sediments are coarse (cobble dominant) and in places >3m thick; most sedimentary structures have been destroyed. The last remnants of terrace C in this reach are found downstream of Los Olivillos where outcrop is patchy and difficult to access.

4.2.5 Terrace D and E

4.2.5.1 The Terrace Record

Terrace D is the youngest of the 4 main terrace units preserved across the drainage basin of the Rio Alias and is spatially persistent throughout the Lucainena sub-reach. Terrace E is a minor component of the terrace record, commonly associated with modern floodplain development and has very limited preservation across the drainage basin. With exception of the Lucainena village stream and the transverse reach, terrace D is generally associated with an incisional level below that of the modern system and a terrace surface generally situated between 5-10m above the modern channel. Terrace E is also associated with an incisional level below that of the modern channel and an aggradational height of between 0 and 5m (though generally <3m).

The incisional base of terrace D around the Lucainena village stream is c.2-3m above the current river channel suggesting the Lucainena stream did not incise to a local base-level consistent with that of the rest of the fluvial system. The late development of the strike stream (post terrace B times) and the wide valley associated with terrace C (Figure 4.2.4) suggest a meandering channel belt stripping the Tortonian sands and marls from the valley with lateral erosion dominating over vertical incision. During the incisional event following the aggradation of terrace C, the valley became increasingly confined allowing vertical incision to dominate. It would appear the base-level fall at the area around Los Banos had not yet propagated upstream thus explaining the decreased level of incision associated with terrace D.

Downstream of Los Banos good outcrop of D age sediments is limited, however it is clear that the incisional level is below that of the current river channel. As the Rambla de Lucainena crosses the mountain front and joins with the Rambla Honda the association between terrace D and the older terraces changes. D age sediments bury both terrace stages B and C. The sediments reflect an increase in the supply of hillslope material and the development of valley-side alluvial fans de-coupled from the main stream (Figure

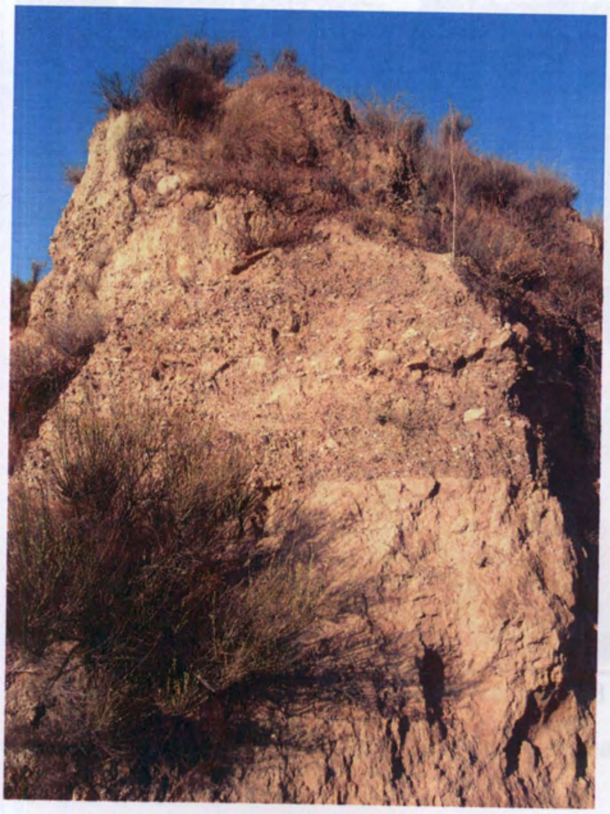


Figure 4.2.12. Terrace C on the R. del Penoncillo. Fine grained terrace C deposits reflecting loss of drainange to the Lucainena village tributary.

Figure 4.2.13. Groundwater calcrete development associated with terrace C at the Rambla Honda/Lucainena junction, the gravels are up to 7m thick.

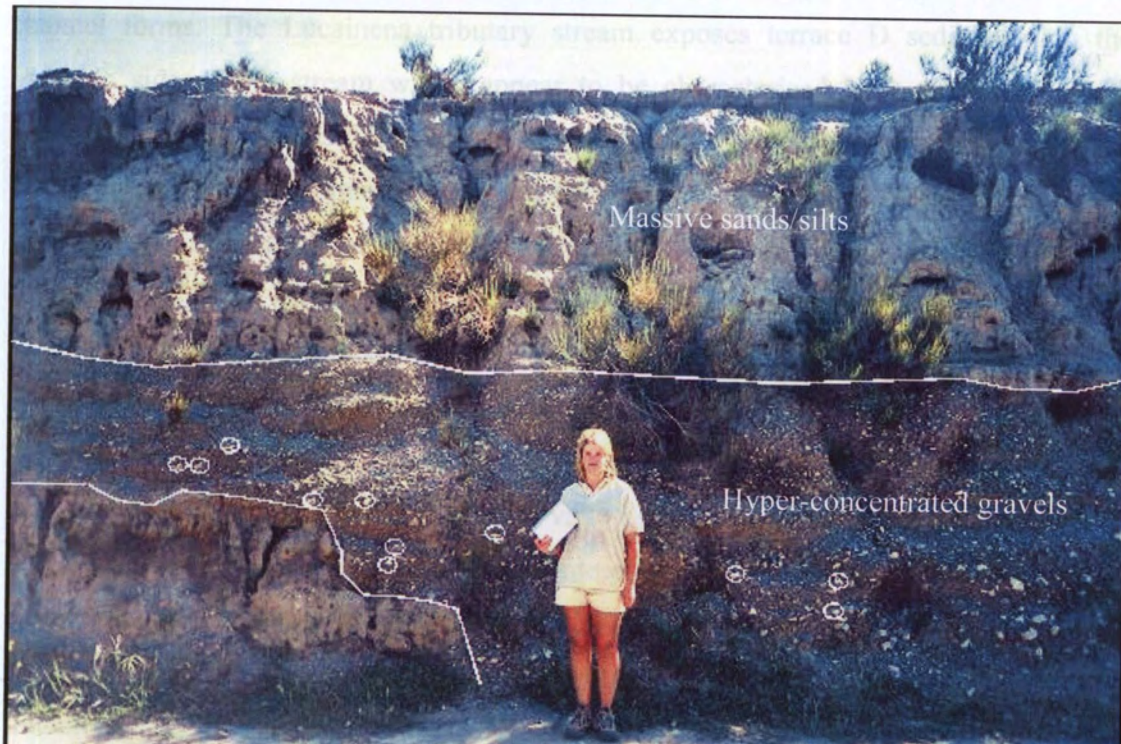


Figure 4.2.14. Terrace D sediments: overlying B and C age deposits. Deposits range from massive sandy/silty units (top of sequence) to matrix supported hyper-concentrated gravel

4.2.14). The fan complex is complicated with several phases of development apparent both upstream and downstream of Los Olivillos.

Terrace E remnants are extremely patchy and often on a scale too small for mapping. The best preservation of terrace E is in the area of Lucainena village (Figure 4.2.2 and 4.2.4) at c.3m above the modern channel. The picture is complicated somewhat in this area as anthropogenic influence has modified the Holocene landscape through both settlement/grazing and mining of local iron ore, and the effects of this upon local landscape development are not clear.

4.2.5.2 Sedimentological Analysis

Sedimentological analyses of gravels associated with terrrace D is restricted, due to poor outcrop preservation throughout the Lucainena sub-reach. Vegetation has often colonised degraded slopes and prevented the architectural analysis of the sediments in any detail. General observations of the deposits in the upper headwater areas suggest sand-gravel streams dominated by sheetfloods (deposition possibly as longitudinal bars) with small channel forms. The Lucainena tributary stream exposes terrace D sediments on the southern side of the stream which appear to be characterised by hyper-concentrated hillslope deposits towards the top of the sequence and channelised gravel deposits at the base (Figure 4.2.15). Sediments deposited further away from the mountain slope record an increased abundance of channelised deposits with subordinate sheetflood/hyper-concentrated flows at the top of the sequence. The terrace assemblage and sedimentological expressions suggest the terrace D valley had become confined relative to the terrace C valley and the input of slope material had increased.

Downstream of the Rambla Honda confluence terrace D age deposits burying B and C age sediments are well exposed along the valley side. The sediments are dominated by silty-sandy massive sediments with gravel intercalations. The gravel units are erosively cut into the finer units and are disorganised with few sheetflow structures and range from tractional to hyper-concentrated flows (Figure 4.2.14). The deposits are up to 5m in thickness.

Terrace E sediments are not exposed sufficiently to allow sedimentological analyses of outcrops but appear to be composed predominantly of silty material.

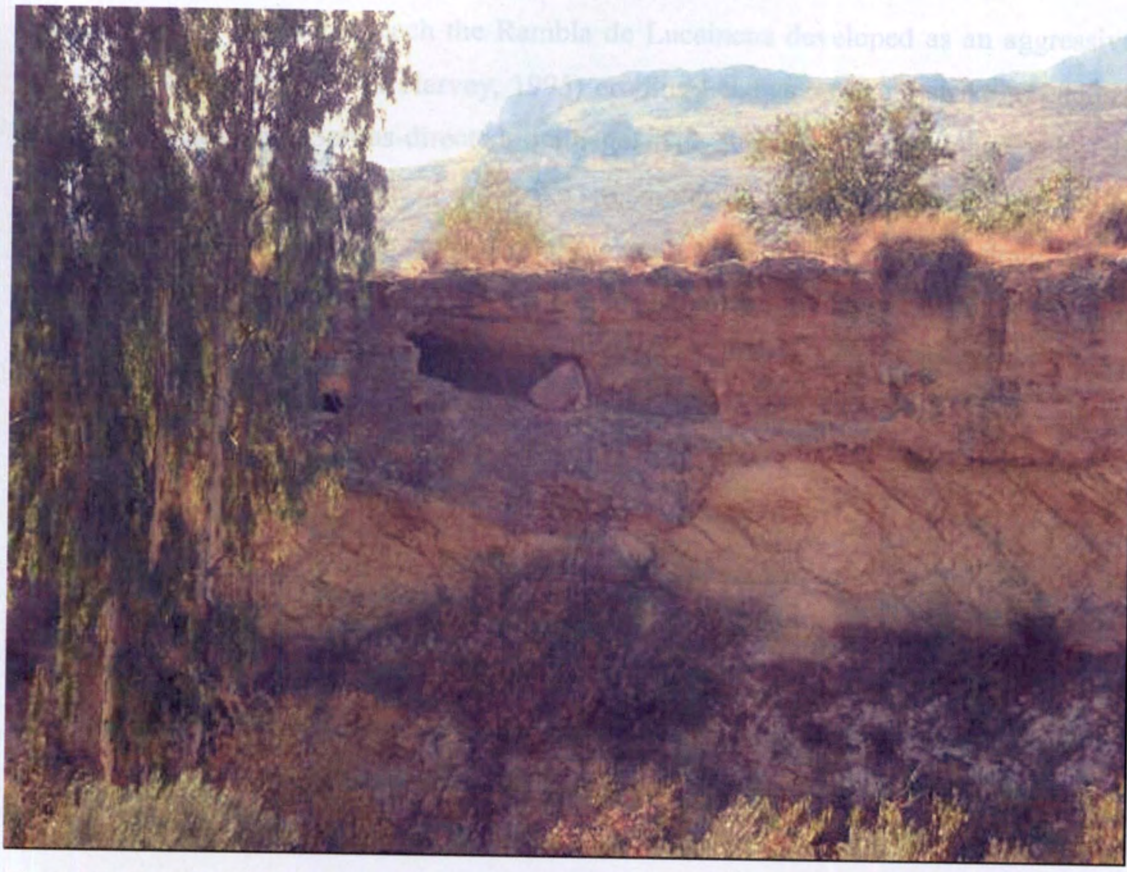


Figure 4.2.15. Terrace D deposits upstream of Lucainena village. The bottom of the section is characterised by channelised deposits, and the top of the sequence by hyper-concentrated flows.

4.2.6 Palaeo-environmental Synthesis

4.2.6.1 Terrace A

The geomorphic assemblage throughout the Lucainena sub-reach suggests development of extensive pediment surfaces sloping away from the hillslopes of the Sierra Alhamilla and the Risco de Sanchez with local incision and channelisation of the fluvial system in the central portions of the headwater area (terrace A2). Downstream, around the transverse reach of the Rambla de Lucainena, little of terrace A is preserved, consequently understanding the evolution of the downstream portion of the system is limited. Downstream of Los Olivillos a sloping strath that appears to correlate with stage A is preserved and displays similar form to the sloping pediments of the assemblage around the Lucainena area, suggesting a similar development of the early drainage throughout the basin.

Upstream of the transverse reach the Rambla de Lucainena developed as an aggressive subsequent stream (Mather & Harvey, 1995) eroding headwards along strike to capture early Plio-Pleistocene Sorbas-directed drainage. The terrace A assemblage suggests further headwards development of the strike stream during its early incisional evolution. As indicated by Figure 4.2.2, several of the extensive pediment surfaces slope to the north-west into the Sorbas/Tabernas basins suggesting that at that time the uppermost Lucainena headwaters fed into the Sorbas basin. Headwards expansion of the river after the post-terrace A incision appears to have ceased.

4.2.6.2 Terrace B

The incisional event following terrace A led to confinement in most parts of the fluvial system and the headwards erosion of the Rambla del Penoncillo to its modern position. The slopes feeding sediment from the Riscos de Sanchez to the north appear pediment-like in their morphology, however the deposits thicken into the central area of the basin and become confined into relatively smaller valleys. A series of strath remnants suggest that drainage from the Alhamillas directly behind Lucainena village was heading in a northerly direction feeding small tributaries into the Rambla del Penoncillo. This suggests that the Lucainena village stream had not developed during terrace B times (the area most affected by the proposed capture will be discussed in detail in the section 4.2.6.3). These feeder streams were incised into small confined valleys and had individual drainage areas fed from the mountain slopes.

Downstream the system appears to have been behaving as an incised meandering channel system, with a large abandoned meander as the last remnant of the B age river course before the transverse reach. Terrace B is preserved in the area surrounding the Rambla Honda junction and is suggestive of a channelised valley belt.

As has already been discussed, the incisional level of the base of terrace B is variable from the headwaters to the transverse reach (18m-c.5m above the modern channel: Figure 4.2.3). The tapering of the terrace levels towards the Sierra Alhamilla axis suggests uplift of the mountain belt during the incisional event preceding aggradation of terrace B. However, terrace B sediments show no evidence of syn/post-sedimentary deformation to infer any localised fault activity associated with the trans-pressional uplift of the mountains. Deformation during and following deposition of the Sorbas-basin Gochar formation was at its greatest on the southern margin of the basin suggesting rapid uplift of the mountains, but it is difficult to assess the persistence of this activity as terrace A is only fragmentary. Terrace C also suggests a phase of possible uplift, though of a limited amount. It is clear that throughout Gochar times and through terrace A and B times, uplift was ongoing and affecting fluvial development on the edge of the basin.

4.2.6.3 Terrace C

The good preservation of terrace C throughout the basin allows a detailed palaeo-environmental reconstruction for the evolution of the system during this period. In the headwater area a minor river capture has been proposed following the aggradational event of terrace B on the basis of the terrace assemblage at river stage B. Terrace C remnants have been analysed in the area proposed to have lost a portion of its headwaters (see Figure 4.2.2) in order to try to determine any capture-related loss of stream power.
The preserved sediments associated with terrace B are a coarse conglomeratic unit of c.2m thickness. The sedimentary architecture of terrace C age gravels reflects a stream carrying a much finer load dominated by sand units with gravel intercalations, sheetflood deposits and small channel structures. The deposits hint at a decrease in relative stream power, however the change in process-related bedform morphology is not entirely conclusive as it may relate to the new input of tributary eroded fine-grained Tortonian bedrock. This turbidite/marl unit is very fine grained and rarely erodes to clast fragments, generally entering the system as suspended material. The interbedded sandstones do however remain in clast form for a short period downstream. However, the combined analysis of the geomorphic assemblage and the sedimentological characteristics do suggest a minor capture event. Clast lithology variation between the units (to be discussed in detail in Chapter 5) is limited in its application to this area as both streams source the same material. However there is a significant decrease in the locally sourced Iron Ore unit from 25% in terrace B to 16% in terrace C. Although both modern streams (Lucainena village stream and the Rambla del Penoncillo) drain the iron ore unit the major zone of iron ore material is located to the west of Lucainena village and would, without previous mining activity, form a major source to the Lucainena village stream and a secondary source to the Rambla del Penoncillo. Consequently the decrease in content of iron ore between terraces B and C on the Rambla del Penoncillo builds on the

previous geomorphic and sedimentological evidence to support a drainage re-organisation event.

The terrace assemblage in the Lucainena village tributary reflects development from C times only. A sloping pediment associated with terrace A borders the valley but relates to earlier north-east flowing drainage. The straths associated with terrace B are oblique to the modern drainage system. The proposed driver of the capture is a local base-level change in the area downstream of Los Banos. There is little preservation of terrace B and no post-depositional deformation can be observed, however, the incisional base of terrace C is abnormally close to the modern channel in this area (between 0 and 1m above the channel) and there is no apparent deformation of the C sediments. Directly opposite this anomalous zone a tributary is developed within a heavily cemented ground water calcrete. This zone follows the orientation of a well documented lineament that has been active throughout the Plio-Pleistocene and up until the Holocene, the Infierno Marchalico Fault (Mather & Westhead, 1993; see Figure 1.2). The structural lineament lies on a northeast-southwest line, the direction followed by the alignment of the anomalous C sediments and the tributary developed in the groundwater calcrete. In a downstream direction the incisional base-level of terrace C gradually returns to normal (2-3m), the aggradational level of the terrace surface is consistent throughout the reach. The amalgamation of evidence from across the area suggests a tectonic lowering of base-level in the area downstream of Los Banos prior to the deposition of terrace C caused a second strike-stream to develop through Lucainena village and consequently beheaded the Rambla del Penoncillo. The exact timing of this event is difficult to ascertain due to lack of outcrop, however, it can be limited to the final phase of aggradation of terrace B or during the following incision before deposition of terrace C sediments.
The architectural analysis of the sediments suggests a gravel dominated braided stream characterised by a sequence of stacked channels, meandering across a fairly wide valley floor. As the system moves through the boundary fault into the transverse reach there is some suggestion of possible uplift of the Sierra's as the base of terrace C falls to between 1 and 2m above the current channel, 1-2m lower than in the headwater areas. The sediments are relatively coarse but little can be determined in terms of environmental

process as an extremely thick ground water calcrete has developed and obliterated all sedimentary structures.

4.2.6.4 Terrace D and E

The fluvial system development during the late Quaternary and the Holocene appears to be similar to today's, with the exception of the Lucainena village tributary and the area around Los Olivillos. The available sections/exposures indicate a gravel-bed river with dominant movement by sheetflood processes and small channelised flows. The terrace assemblage suggests a gradual evolution towards the present day system with no drainage re-organisation, or valley abandonment suggested. Meander patterns of terrace D suggest gradual evolution towards the modern channel form.

Poor preservation of terrace E prevents detailed reconstruction of river/valley form and process. This is further complicated by the anthropogenic impact associated with grazing of the land and, more importantly in this area, mining of local Iron Ore. Terraces have been bulldozed, artificially created for the development of the local railway line (now abandoned) and many subtle Holocene features have been destroyed or become unreliable indicators of river development.

4.3 The Polopos Sub-Reach

4.3.1 Introduction

The Polopos sub-reach is defined by structural features and major landforms. The boundary fault on the southern side of the Sierra Alhamilla essentially forms the upper limits of the basin for this study where the Rambla de Lucainena exits the canyon. Fluvial depositional remnants are not observed through the canyon until the area around Polopos village (GR: 5806 40977, Sheet 1031-III). The eastwards limit of the basin is essentially structurally controlled by an anticline probably associated with the Carboneras Fault Zone formed in the Neogene basin sediments. At this point there is a long established nickpoint (GR: 5898 40948, Sheet 1046-II). The terrace sequence is relatively straight-forward throughout this sub-reach with little obvious major local tectonic activity affecting the evolution of the system within this reach. There is also evidence of Late-Quaternary movement along the boundary fault of the Sierras (Harvey and Wells, 1987), associated with the major uplift of the Sierras. In the Polopos sub-reach the Rio Alias has two major transverse tributaries developed, the Rambla de los Feos the beheaded remnant of the original Aguas/Feos Sorbas basin master drainage, and the Arroyo Gafares another transverse drainage rising in the southern margin of the Sorbas basin. The general defining characteristics of the Alias terrace assemblage are presented in Table 4.2.

Terrace	Height of Terrace Surface	Incisional Level	Calcrete Development	Soil RI	Cementation/ Induration
A	30-50m	20-45m	4-6	N/A	Cemented and indurated
B	15-20m	15-18m	4-5	N/A	Cemented and indurated
C	10-20m	5-10m	3	5	Cemented some induration
D	c.10m	*	0	0.8	Loose sediment
E	0-5m	*	0	N/A	Loose sediment

Table 4.2 Terrace characteristics for the Polopos sub-reach. Calcrete and soil development after Gile et al., (1966), Machette (1985) and Harvey et al., (1995).

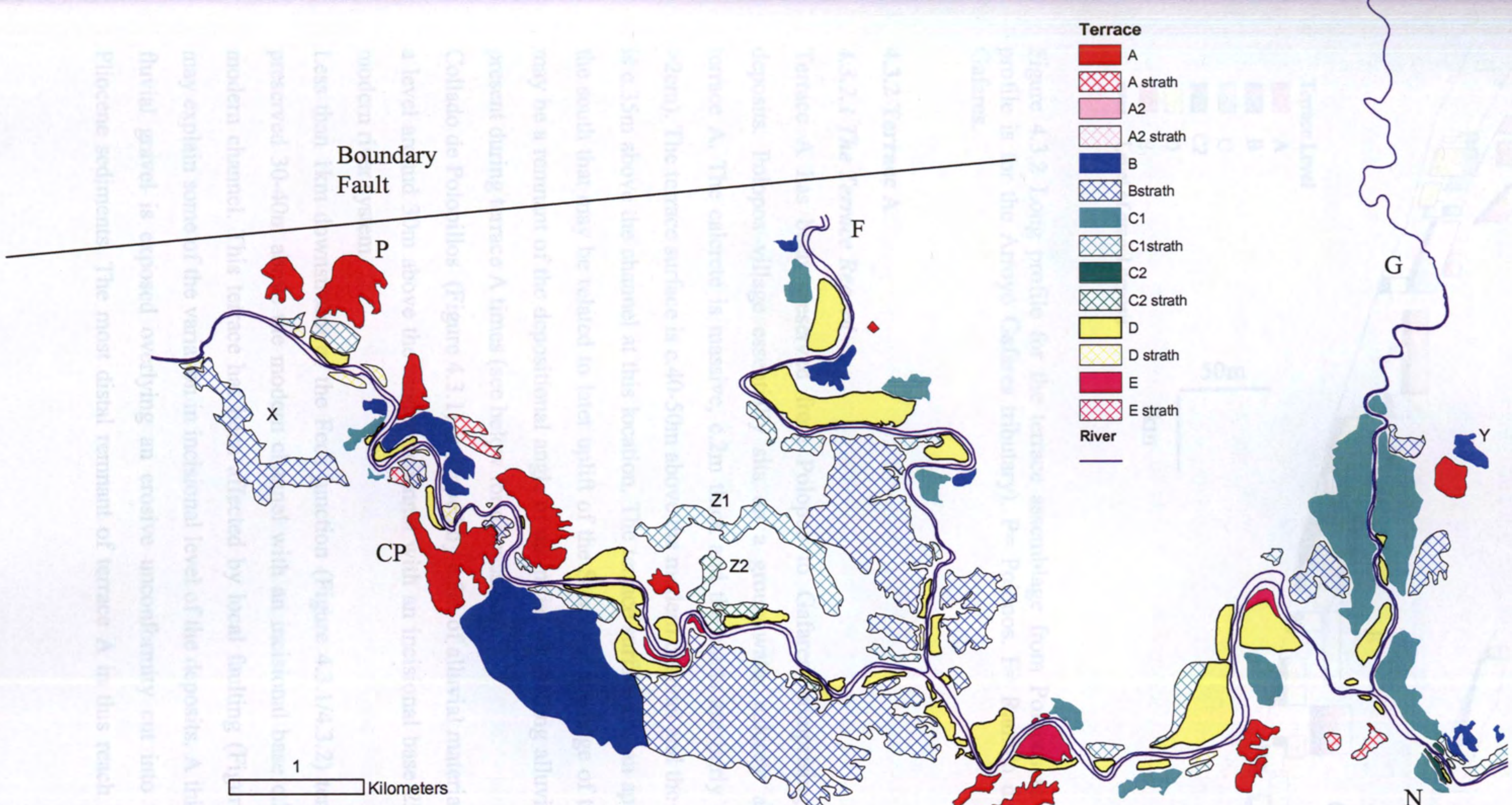


Figure 4.3.1 Terrace map of the Polopos sub-reach. F= Rambla de los Feos. G= Arroyo Gafares. P= Polopos. N= Nickpoint. CP= Collado de Polopillos. For other locations refer to text.

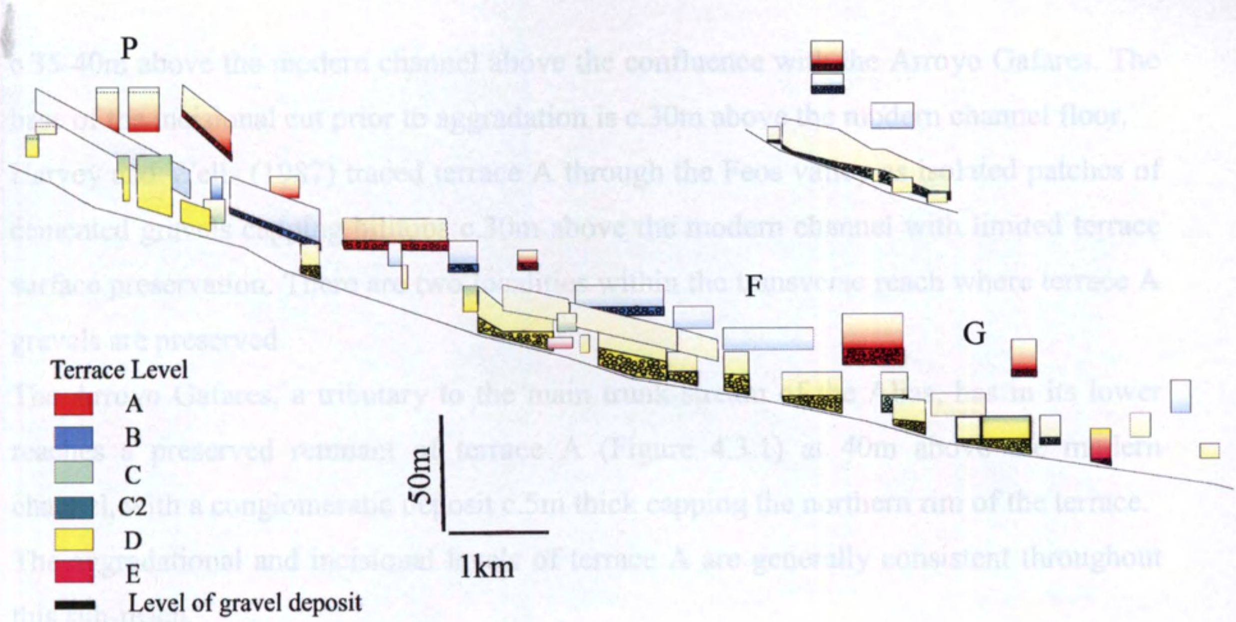


Figure 4.3.2 Long profile for the terrace assemblage from Polopos to Gafares (inset profile is for the Arroyo Gafares tributary). P= Polopos. F= Rambla de los Feos. G= Gafares.

4.3.2 Terrace A

4.3.2.1 The Terrace Record

Terrace A has been preserved from Polopos to Gafares, comprising gravel/cobble deposits. Polopos village essentially sits on a groundwater calcrete associated with terrace A. The calcrete is massive, c.2m thick and the clasts are fairly coarse (B axis >2cm). The terrace surface is c.40-50m above the modern channel and the incisional base is c.35m above the channel at this location. The terrace surface has an apparent slope to the south that may be related to later uplift of the Sierras at the edge of the valley, or it may be a remnant of the depositional angle of an initial prograding alluvial fan that was present during terrace A times (see below for discussion).

Collado de Polopillos (Figure 4.3.1) is capped by c.5m of alluvial material that grades to a level around 30m above the modern channel with an incisional base 25m+ above the modern river system.

Less than 1km downstream of the Feos junction (Figure 4.3.1/4.3.2) terrace A is well preserved 30-40m above the modern channel with an incisional base c.20m above the modern channel. This terrace has been affected by local faulting (Figure 4.3.3) which may explain some of the variation in incisional level of the deposits. A thick sequence of fluvial gravel is exposed overlying an erosive unconformity cut into the underlying Pliocene sediments. The most distal remnant of terrace A in this reach is preserved at c.35-40m above the modern channel above the confluence with the Arroyo Gafares. The base of the incisional cut prior to aggradation is c.30m above the modern channel floor. Harvey and Wells (1987) traced terrace A through the Feos valley as isolated patches of cemented gravels capping hilltops c.30m above the modern channel with limited terrace surface preservation. There are two localities within the transverse reach where terrace A gravels are preserved.

The Arroyo Gafares, a tributary to the main trunk stream of the Alias, has in its lower reaches a preserved remnant of terrace A (Figure 4.3.1) at 40m above the modern channel, with a conglomeratic deposit c.5m thick capping the northern rim of the terrace. The aggradational and incisional levels of terrace A are generally consistent throughout this sub-reach.

4.3.2.2 Sedimentological Analysis

Terrace A throughout this sub-reach is composed of conglomeratic deposits several metres thick. Extensive groundwater calcrete development throughout the terrace A deposits underlying the village of Polopos has prevented any sedimentological analysis of alluvial structures. The only general observation to be made is that the material is conglomeratic with clasts with B (intermediate) axis of 2cm+.

The sediment sequence preserved in the gravel quarry at Collado de Polopillos, c.3km downstream, is different (Figure 4.3.4). In this location the terrace A conglomerates appear to be almost conformable with the underlying Polopos formation (of Mather, 1991; 1993b) with relatively little erosion into the lower unit. Sediment grain size characteristics are radically different from the Polopos Formation. Sediments are dominated by gravels and sands with subordinate coarse units (B axis up to 15cm) and thick accumulations of sandy/silty layers. Erosive scours are preserved in places often marking a new event beginning with a coarse unit and followed by a fining up sequence. Vertical aggradation in horizontal sheets that may pinch out laterally are common, with channel structures present but limited in size. The majority of the sediments have been deposited under tractional flow conditions; however there is some indication of hyper-concentrated flows in places, suggested by the floating nature of several clasts (Figure 4.3.4).

Terrace A downstream of the Feos junction and beyond cannot undergo detailed sedimentological analysis due to outcrop location and inaccessibility of the 35-45m cliff

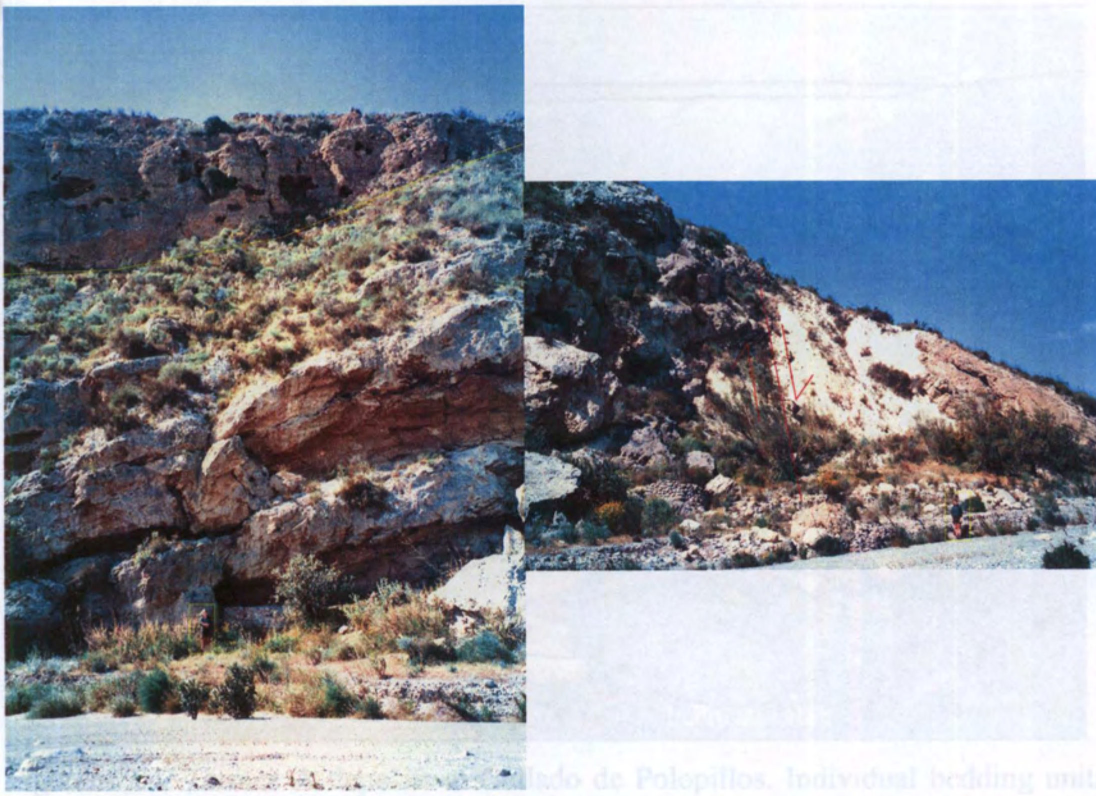


Figure 4.3.3. Terrace A downstream of the Feos junction. Yellow line indicates erosional unconformity between terrace A sediments and Neogene bedrock. Red line on the second photo indicates fault plane and associated direction of movement, yellow boxes enclose person for scale of 1.7m.

faces. However it can be seen that the deposits are associated with large scale erosion surfaces developed into the underlying strata (Figure 4.3.4). The deposits are conglomeratic with coarse intercalated sand/gravel layers and channel structures that can be inferred by viewing the section from a distance of c.50m. The sequence is capped by a mature stage 6 pedogenic calcrete (after Machette, 1985).

4.3.3 Terrace B

4.3.3.1 The Terrace Record

Terrace B forms the most persistent terrace surface throughout the Polopos sub-reach covering an area of c.3km^2 in the central portion. The aggradational height of terrace B is generally c.15-20m above the modern channel and this is consistent across the sub-reach. Terrace B when capped with alluvial material is associated with an incisional cut of c.15-18m above the modern channel. Sediments preserved on B age surfaces around Collado de Polopillos (Figure 4.3.5) are 2-4m thick with indiscernible sedimentary structures. The

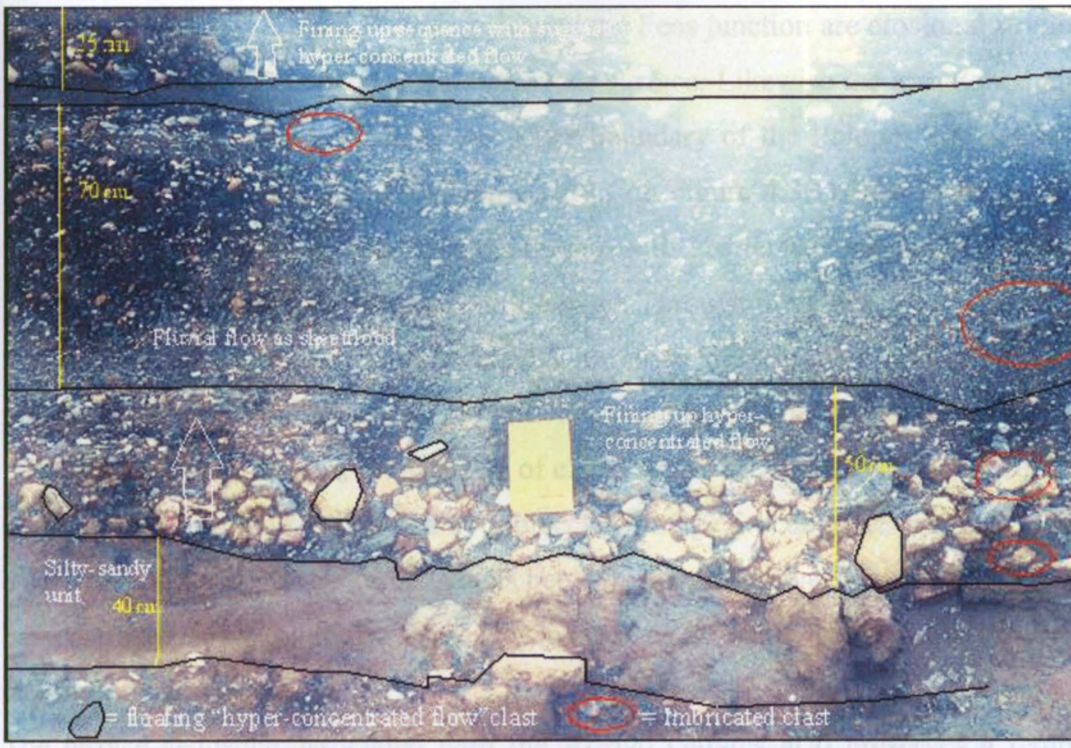


Figure 4.3.4. Terrace A deposits at Collado de Polopillos. Individual bedding units are indicated by black lines.

Figure 4.3.5. Terrace level B indicated by level of plastic green housing.

portions of the main terrace B surface around the Feos junction are erosional straths, with any original deposits stripped from the terrace surface. Likewise the abandoned meander associated with terrace level B at the upper boundary of the Polopos sub-reach has no associated deposits and is an erosional form (x on Figure 4.3.1). The lower Feos valley has also been mapped to establish continuity with the terrace sequence of Harvey & Wells (1987) for the proto-Aguas/Feos drainage. Through the lower portion of the valley terrace B is preserved and is associated with strath development c.15-20m above the modern channel. Small patches of alluvial sediment associated with terrace B are preserved and record an incisional level of c.20m above the modern channel. Terrace B is characterised throughout this area by a brecciated stage 5 pedogenic calcrete, suggesting a reliable continuity of the terrace levels between the Sorbas basin and the Almeria basin, based on previous work in the Sorbas basin (Harvey & Wells, 1987; Harvey et al., 1995) and the current study.

The terrace sequence associated with the Arroyo Gafares also preserves a remnant of terrace stage B that forms an abandoned meander (y on Figure 4.3.1). The aggradational level of terrace B is c.30m above the modern channel with an incisional level c. 25m above the modern channel.

4.3.3.2 Sedimentological Analysis

Stage B deposits are best preserved around Collado de Polopillos, they are however generally <3m in thickness and detailed sedimentological analysis is not possible due to lack of outcrop and the degradation of the deposit. The preserved sediments suggest a dominantly coarse load as clasts are generally pebble/cobble size with subordinate sand intercalations. The terrace sequence around the Feos junction preserves little or no alluvial material on the distal portion of the major B terrace (Figure 4.3.6). What deposits there are are unconformable with the underlying strata and appear to be fully tractional in nature (clast supported).

4.3.4 Terrace C

4.3.4.1 The Terrace Record

Terrace C in the central portion of the basin is an important terrace as it marks the final stage of the proto-Aguas/Feos through drainage. Terrace remnants are preserved both upstream and downstream of the Feos junction. In the area around Polopos terrace remnants are limited in extent and lie at around 10m and 15m above the modern channel.

Figure 4.3.6. Terraces B and D at the Alias/Feos junction. View to the north.

This is the lowest level at which the C terrace is found and this may relate to tectonic activity lowering the unit, or lowering the local base-level. Alternatively, these sediments could be of terrace D age, an unlikely possibility because the sediments are well cemented and indurated (Figure 4.3.7), a stage of development not seen in D age sediments elsewhere throughout the region. The sediments therefore appear to be C age and the terrace surface an erosional remnant formed later during terrace D times. Due to limited outcrop and no obvious evidence of tectonic activity (i.e. actual faulting of the unit) it is difficult to ascertain the unequivocal reason for this slightly lower than expected terrace level (this will be discussed further in section 4.3.6).

A little further downstream, but upstream of the Feos junction the terrace C sequence becomes a little more complicated with 2 stages of development (Figure 4.3.1), C1 and C2. C1 is the first stage of development and forms an abandoned meander at approximately 20m above the modern channel (Z1 on Figure 4.3.1). This is a relatively large meander loop preserved as a strath set below terrace B and must have been the active course of the river for a significant period of time to allow development of a large river valley. C2 is preserved as a strath c.15m above the modern channel and is defined by a much smaller valley that appears to follow the upper course of C1 but cuts off the

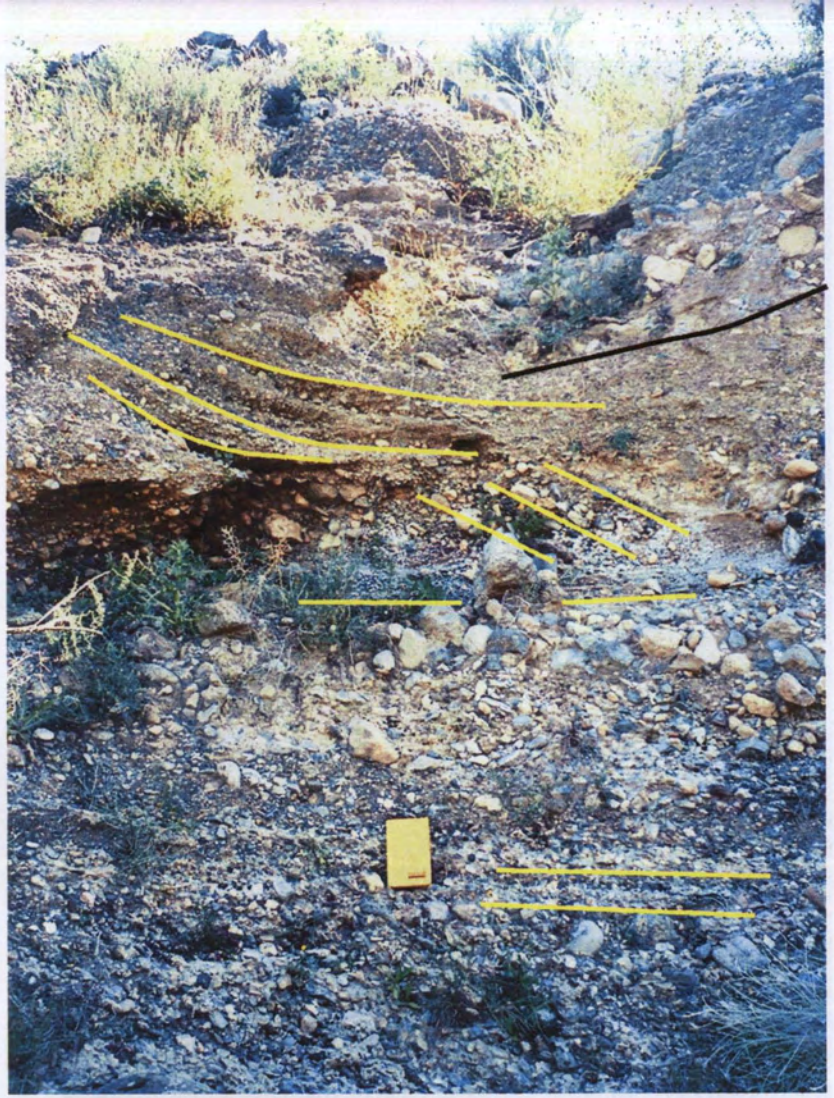


Figure 4.3.7. Terrace C on the Rio Alias, downstream of Polopos. Thick yellow lines indicate foreset development and horizontal aggradational surfaces. Black line indicates large channel scour.

Figure 4.3.8 A and B. A= C1 palaeo-meander developed (view to the south). B= Terrace level C2 cut below terrace C1. Arrow indicates route of the palaeo-channel.

large meander loop to exit via a narrow valley cut into bedrock (Z2 on Figure 4.3.1) set above terrace D (Figure 4.3.8).

Downstream of the Feos junction terrace C is preserved with an aggradational surface 15-20m above the modern channel and an incisional cut 6-8m above the modern channel. The terrace is capped by a pedogenic calcrete exhibiting stage 3 calcrete development (nomenclature after Machette, 1985). Up to 12m of sediment has been preserved in section that allows detailed analysis of alluvial architecture within the deposits (see below). Above the tributary junction of the Arroyo Gafares terrace C is preserved in 2 locations at c.15m above the modern channel with an incisional base of between 5 and 7m above the modern channel. Section preservation is poor with only a thin veneer of sediment on one terrace and 2m of sediment on the other.

Terrace C forms an extensive surface within the valley cut by the Arroyo Gafares. At the valley edges the terrace appears to slope in from the hillslopes beginning at a level c.20m above the channel. Immediately adjacent to the channel the terrace surface is between 7 and 10m+ above the modern arroyo (Figure 4.3.9). Calcrete preservation is poor but small patches remain in places and generally suggest stage 3 development. This, however, is complicated by the development of extensive groundwater calcretes in places.

Figure 4.3.9. Terrace assemblage on the Arroyo Gafares.

Figure 4.3.10. Terrace C on the Rio alias downstream of the Feos junction. Thick yellow lines mark large erosional surfaces/channel structures. Light yellow lines indicate vertical and horizontal aggradational surfaces.

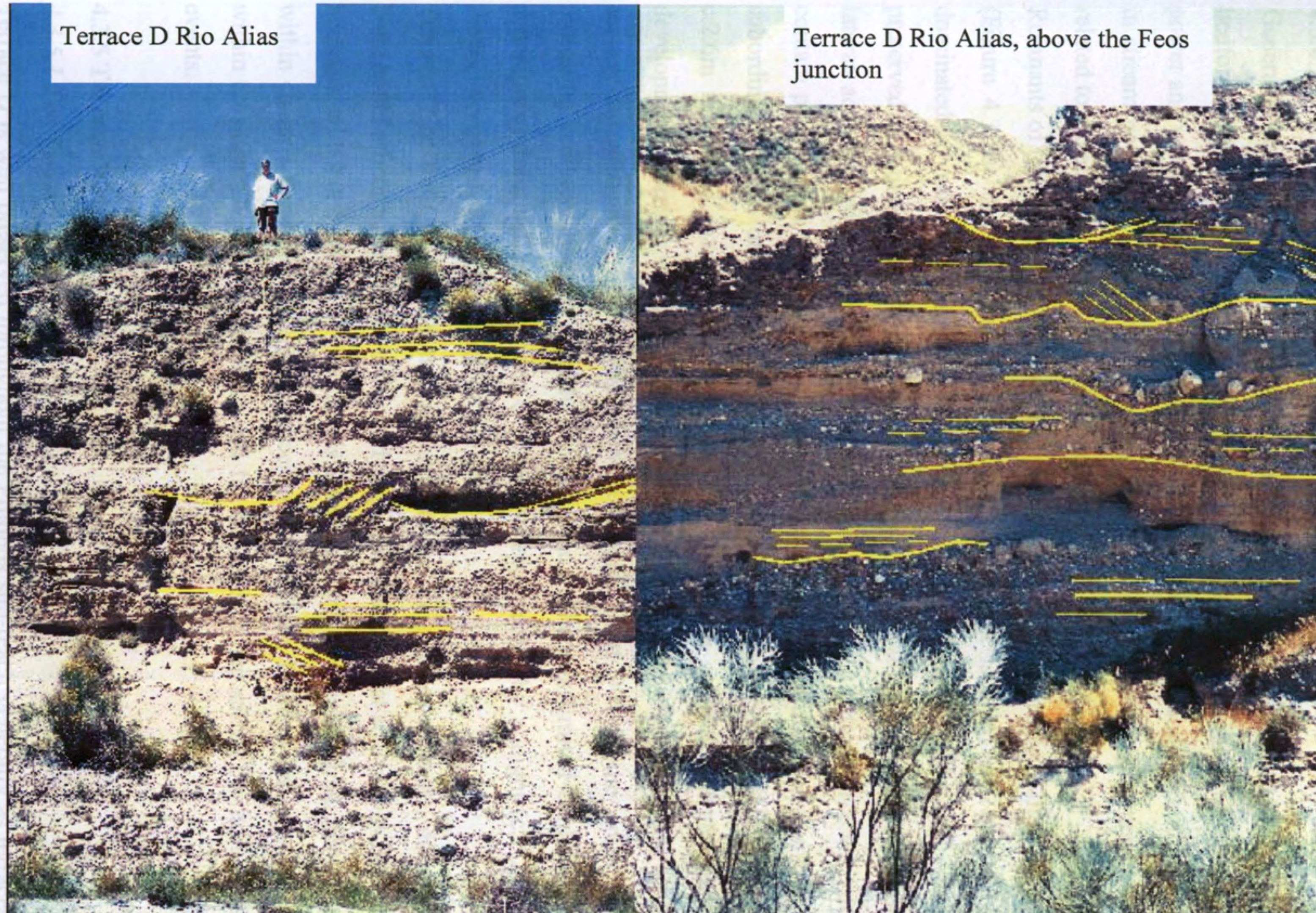


Figure 4.3.11. Terrace D on the Rio Alias upstream (right) and downstream (left) of the confluence with the Rambla de los Feos.

4.3.4.2 Sedimentological Analysis

General sedimentological features were noted with particular reference to clast size and bedform geometries. Bedform geometry was used as a useful indicator of relative stream power and water depth, consequently allowing inferences to be made regarding variations in stream power between terraces in this location and therefore to changes that can be related to the effects of the Aguas/Feos capture.

Remnants of terrace C were analysed both upstream and downstream of the Feos junction (Figure 4.3.10). Average channel depth and bar height is c.1m and particle size is dominated by sand and gravel grade material. Cross bedded sands and gravels are preserved and limited imbrication within the gravel is at 90° to the foresets, indicating lateral accretion of point bars. Downstream of the Feos junction terrace C deposits contain planar cross stratified conglomerates, horizontally stratified conglomerates (and subordinate sands) and large palaeo-channel structures. Average channel depths of c.2.6m imply the channel geometry was large requiring substantial water depths for development. Foresets with average heights of c.2.5m are developed oblique to channel scours and associated clast imbrication is developed at 90° to the cross bedding, indicating sedimentation as laterally accreting bars. There is limited evidence of syn-depositional deformation of terrace C sediments represented by a slight (c.1-2m) fall in the incisional base of the deposits.

Terrace C on the Gafares tributary is characterised by c.3m of deposits, dominated by large boulder beds scoured into the underlying weak marls. Clast size ranges from sand to boulders with 60cm B axis. The unit is dominated by vertical aggradation related to within channel bar development and sheetflood processes. Limited fining up sequences within erosional scours suggest a cut and fill scenario of deposition by individual flood events.

4.3.5 Terrace D and E

4.3.5.1 The Terrace Record

Terrace D is well preserved throughout the Polopos sub-reach generally as terraces with associated alluvial deposits. The terrace height is c.10m above the modern channel and this is spatially consistent across the basin. Terrace D remnants are preserved along the modern channel in the immediate vicinity of Polopos (Figure 4.3.1) as slope and pediment type features grading from terrace level C to D. Downstream the terraces become preserved as independent features with no associated grading between the levels.

Below the Feos junction terrace D is preserved between 7 and 10m above the modern channel (Figure 4.3.11). Throughout the Polopos sub-reach the incisional cut of the gravels is below the present day channel and is not exposed. Furthermore there is no observed calcrete development found on terrace D, only limited pockets of poorly developed brown soils (Table 4.2). Terrace D below the Feos junction exhibits a decrease in valley width post-terrace C times.

Terrace D in the Gafares valley is spatially limited to the area immediately adjacent to the modern stream, forming small terraces whose extent is restricted by the C age terraces developed extensively across the valley. This suggests the river valley at stage D was significantly reduced in breadth compared to terrace C times. The terrace surface is between 7 and 10m above the modern channel and the incisional base of the deposits cannot be seen.

Terrace E is extremely patchy within the Polopos sub-reach. Where preserved the terrace surface is c.5m above the modern channel and is often difficult to distinguish from the modern floodplain. Terrace E is often preserved on the bends of slowly migrating meander loops associated with multi stage development.

4.3.5.2 Sedimentological Analysis

Deposits related to terrrace D are well preserved throughout the Polopos sub-reach allowing process related interpretations to be made. D age deposits upstream of the Feos junction are characterised by the sedimentological assemblage presented in figure 4.3.11. Clasts are generally gravel size, with interbedded sands common. Boulder beds are preserved but are rare. Channel and bar-forms are relatively small, between 0.5 and 1.5m in height, and channels c.3-4m in width and bars 3-5m in width. The sediments are dominated by vertical accretion surfaces and towards the top of the sequence by lateral accretion surfaces. There is no evidence of channel cut and fill within one event, channels are preserved but usually associated with lateral accretion surfaces towards the top of the sequence. Upstream of the Feos junction terrace stage C and D deposits are similar in geometry and style where preservation allows for architectural analysis.

Terrace D gravels downstream of the Feos junction are shown in Figure 4.3.11 and are c.7m in thickness. Clast size is generally gravel size with common intercalations of sand, mud drapes in places and sub-ordinate boulder beds. Bar form relief is low generally 1m and less, and >5m in width. Channel structures are rare and are <1m in height and c.3m in width. Facies associated with vertical accretion dominate the assemblage, convex up *sections within the vertical beds suggest some longitudinal bar development within an* environment dominated by sheetfloods. The relief/geometry of the bed-forms within stage D deposits is the same as the bed-forms preserved within the modern channel belt. Stage D deposits preserved on the large meander bend upstream of the tributary junction with the Arroyo Gafares suggest low angle, low relief lateral bar migration across the valley floor.

Terrace stage D and E sediments along the lower Feos are similar to those along the Rio Alias. The incisional base of terrace D deposits is below that of the modern channel with fluvial gravels (clast supported with channel and bar-forms) preserved. Terrace E is characterised across the sub-reach by silty sediments and an incisional base to the deposits below the modern channel. Fluvial deposits associated with terrace D on the Arroyo Gafares and E deposits throughout the basin are not available for sedimentological analysis.

4.3.6 Palaeo-environmental Synthesis

4.3.6.1 Terrace A

Terrace A remnants are preserved throughout the Polopos sub-reach at locations proximal, medial and distal to the head of the basin. The facies associated with terrace A in the area around Polopos are suggestive of an alluvial fan environment. At Collado de Polopillos stage A sediments are slightly erosive into the underlying Polopos formation deposits but in many places are conformable with the final basin fill fining up sequence. The river at this point appears to be exiting the confined canyon reach and radiating out in the area downstream of Polopos. The sedimentological analysis suggests that the dominant form of sediment transportation is via sheetflood processes, commonly tractional flow with subordinate hyper-concentrated flow. Supporting the notion of a alluvial fan type environment is the higher gradient of terrace A through this upper part of the basin (Figure 4.3.2).

Moving downstream c.4km and the palaeo-environmental setting has changed. There is a clear suggestion of valley entrenchment and confinement downstream of the Feos junction with a large erosional scour into the underlying Neogene basin fill (Figure 4.3.3). Detailed analysis of the A sediments is not possible, however large scale channel structures and coarse clast assemblages can be determined. Further (1km) downstream the last remnant of terrace A also preserves an erosional unconformity into the underlying Cuevas Viejas sandstone again indicating entrenchment of the river valley. Furthermore the gradient of terrace A through this distal portion of the basin is somewhat less than that in the upper part of the sub-reach (Figure 4.3.2).

4.3.6.2 Terrace B

Sediment preservation of terrace B is poor across the basin with many surfaces preserved as strath features or deposits of <3m thickness in inaccessible areas, therefore detailed reconstruction of the palaeo-environment is difficult. However what is clear is that at terrace B times a large river system was in place within a large palaeo-valley. It appears to be less tortuous than later phases of river development. Two abandoned meanders are preserved associated with terrace B times. The first is upstream of Polopos and the second on the Arroyo Gafares (x and y on Figure 4.3.1). Both meanders appear to have been abandoned during the incisional event following the aggradation of terrace B. The lower Feos valley preserves the same record of valley evolution. The surfaces are, to a large extent, associated with strath development, and where sediments are preserved they are limited in extent and suggest a coarse load. The terraces do however suggest a wide palaeo-valley at this stage of the evolution of the lower Feos with a low sinuosity.

Consequently the inferences that can be made regarding palaeo-environmental evolution of the Polopos sub-reach at terrace stage B are limited to the relative size and pattern of the river valley.

4.3.6.3 Terrace C

Terrace C in the central and distal portions of the Polopos basin represents the last stage of through drainage of the proto Aguas/Feos Sorbas drainage into the Almeria basin. As such the area downstream of the Feos junction is important for inferences regarding possible impacts of the capture event on the evolution of this central portion of the basin. The alluvial architecture of terrace C (pre-capture) and terrace D (post-capture) has been analysed to infer capture-related changes in fluvial processes. In order to rule out climatically induced changes as possible causes of variation in alluvial style during terrace C and D, sediments have been analysed on the Rio Alias both upstream and downstream of the Feos junction (Maher et al., in press).

Terrace stage C deposits in the Polopos area are limited in extent but do relate to a fluvial system similar to the modern river in terms of bed-form relief, and are significantly smaller than the preserved geometries associated with terrace C downstream of the Feos junction. The bed-forms preserved in the deposits of terrace C downstream of the Feos junction represent lateral and vertical migration of large scale bed-forms c. 2-3m in height and consequently requiring greater stream power (discharge) and therefore drainage area.

The preserved assemblage downstream of the Feos junction suggests a mobile channel belt dominated by lateral accretion of transverse bars and channels. The terrace assemblage also suggests a valley meandering to the south towards the modern channel position (Maher et al., in press).

4.3.6.4 Terrace D and E

Geomorphological and sedimentological analysis of terrace D deposits across the sub-reach suggest a change in fluvial system processes between terrace stages C and D downstream of the Feos junction. Upstream of the Feos the geometry of the bedforms in terraces C and D is similar. Downstream of the Feos junction however there is a marked difference in the height and depth of the barforms between the two terrace stages (Maher et al., in press).

The deposits associated with terrace C reflect a river system with the ability to entrain and deposit large clasts >50cm in diameter and preserve barforms with up to 3m height. Terrace D deposits reflect a river system akin to the present day system entraining mostly sand and gravel sized particles, with bedforms of up to 1m height but generally between 0.5 and 1m height. As this variation between units is not apparent on the Rio Alias upstream of the Feos junction, it is inferred that the apparent shrinking of the fluvial system must be related to the river capture event in the Sorbas basin beheading the Rambla de los Feos, and depriving the Rio Alias of c.70% of its drainage area (Maher et al., in press). The impact of the river capture event further downstream is difficult to assess due to the localised impact of activity of the Carboneras Fault propagating upstream (see section 4.4). The ephemeral nature of semi-arid streams also limits the impact of capture in a downstream sense, as flood events are spatially variable and may not effect all areas of the system, thus decreasing the likelihood of floods propagating long distances downstream.

Terrace E/floodplain where observable, is dominated by silty deposits through the Feos junction and along the Rio Alias.

4.4 The Argamason Sub-Reach

4.4.1 Introduction

The Argamason sub-reach is influenced to a large extent by the position of both local and regional tectonic structures. The westwards limit of the sub-reach can be thought of as the area around the Gafares tributary junction, immediately downstream of which is a large nickpoint (Figure 4.4.1/4.4.2) cut into sandstones of the Cuevas Viejas formation (GR: 5898 40947, Sheet no. 1046-II). The nickpoint itself is located on the flank of a large anticlinal fold developed in the basin fill sediments. The downstream portions of the system are controlled by the Carboneras Fault Zone and the eastwards limit of the sub-reach is defined by a nickpoint developed into Cuevas Viejas sandstone near the village of Llano don Antonio (Figure 4.4.1).

Terrace	Height of Terrace Surface	Incisional Level	Calcrete Development	Soil RI	Cementation/ Induration
A	c.40-50m	c.35m	4-6	NA	Cemented and indurated
B	20-30m	c.20m	NA	NA	Cemented and indurated
C	10-20m	0-c.15m	3-4	NA	Cemented some induration
D	c.7-15m	*	0	NA	Loose sediment
E	0-5m	*	0	NA	Loose sediment

Table 4.4.1. General characteristics of the Argamason drainage basin terrace assemblage. Calcrete nomenclature following Gile et al., (1966) and Machette (1985). Soil RI following Harvey et al., (1995).

4.4.2 Terrace A

4.4.2.1 The Terrace Record

Only minor patches of terrace A are preserved within the limits of the Argamason sub-reach. A remnant is preserved as an erosional strath (Figure 4.4.1). On the hinge of the (N-S orientated) anticlinal structure (Figure 4.4.3). The height of the terrace surface is around the highest recorded along the Rio Alias, c.50m above the modern channel and is significantly higher than terrace A at the Feos junction. It may well have undergone uplift to the west of Argamason with continued tectonic deformation of the anticlinal structure.

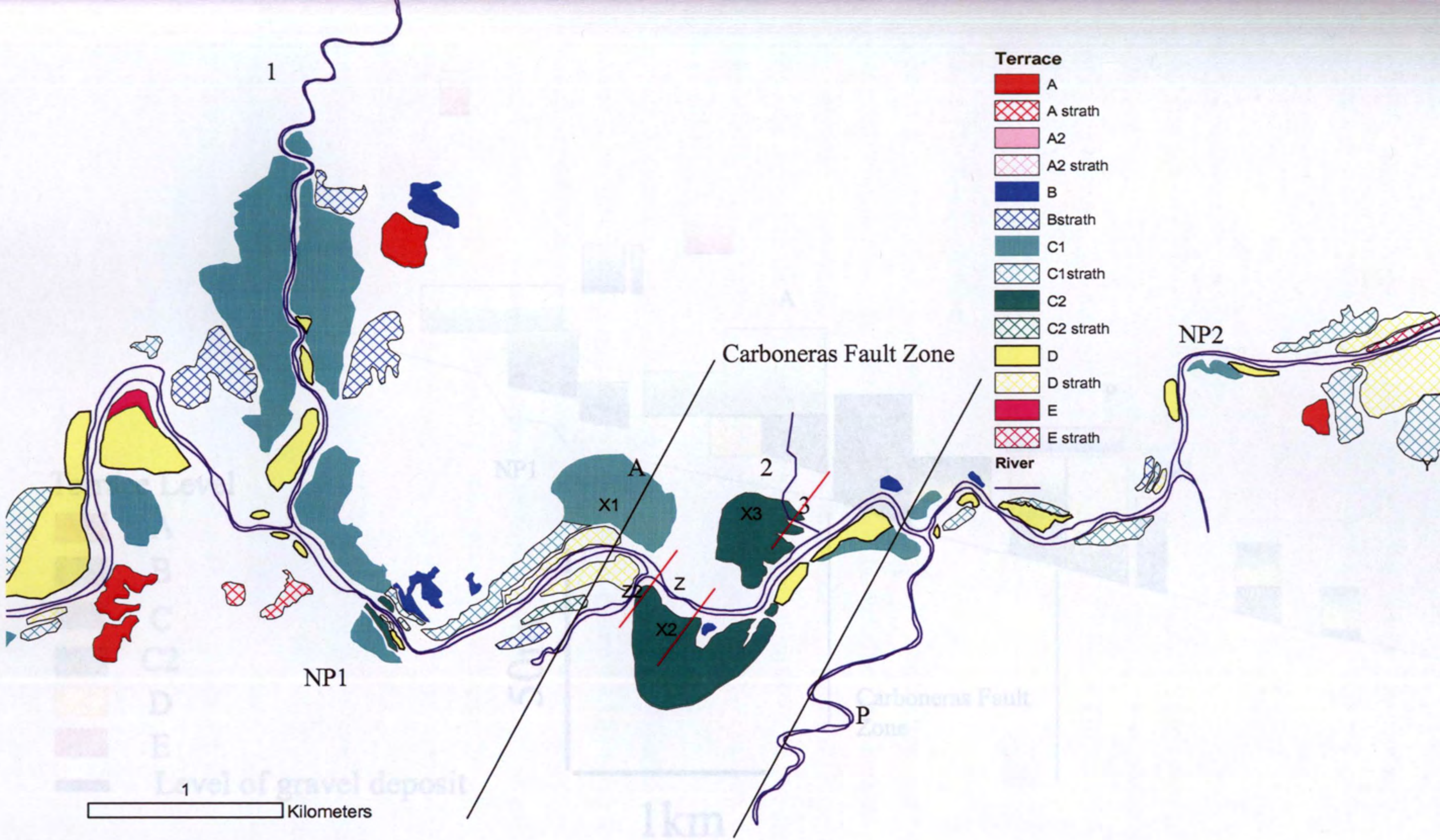


Figure 4.4.1. Terrace map of the Argamason sub-reach. 1= Arroyo Gafares. 2= Barranco del Nagro. 3= Location of D age deformed tributary sediments. NP1= Nickpoint developed at the head of the sub-reach. NP2= Nickpoint upstream of L.D. Antonio. P= Palmerosa tributqry. A=Argamason.For other locations see text. Red lines indicate position of normal faults affecting Quaternary sequence. Black lines de-limit the Carboneras Fault Zone.

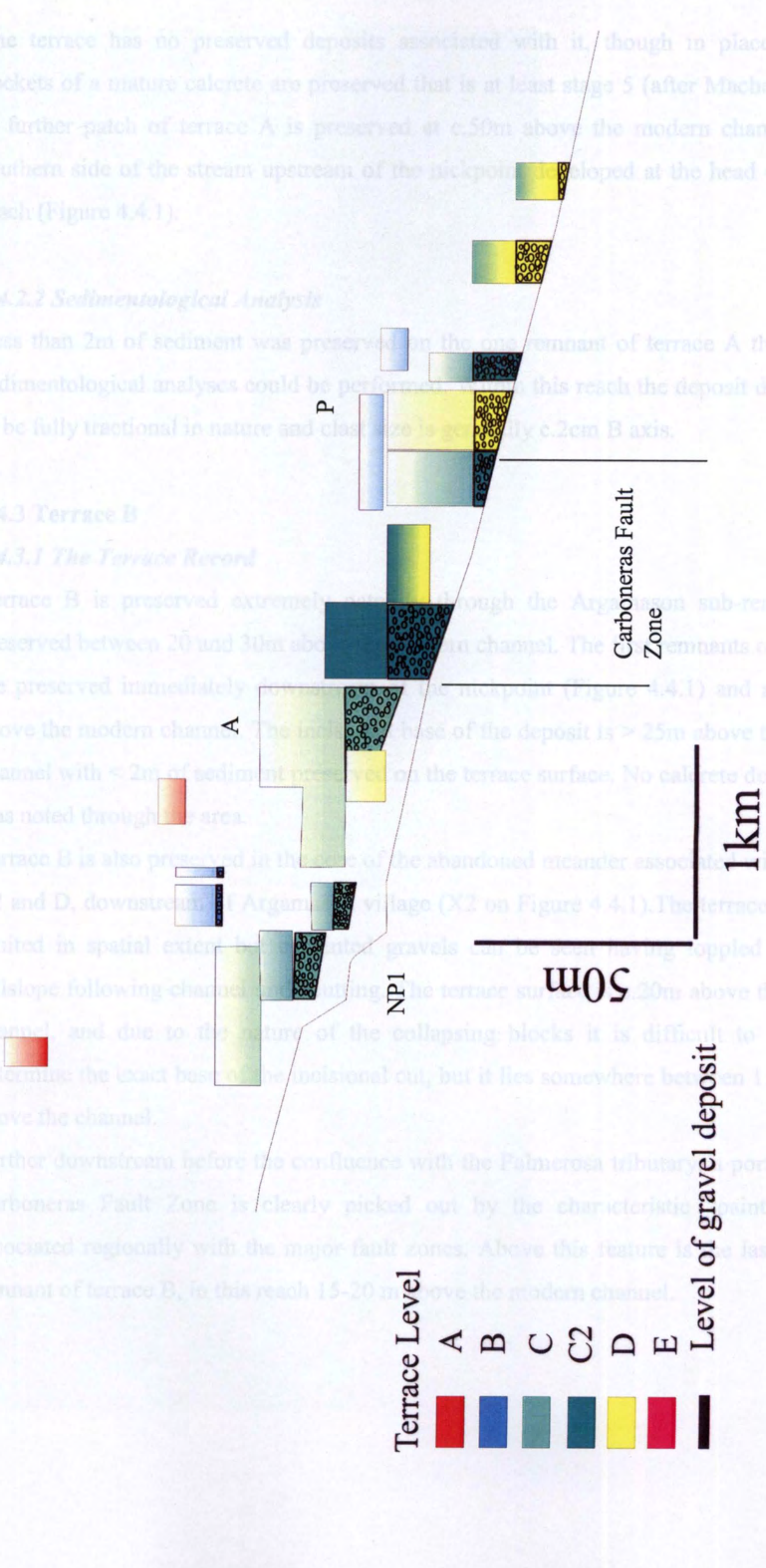


Figure 4.4.2. General long profile for the Argamason sub-reach. A=Argamason village. NP1=Nickpoint at the head of the sub-reach. P= Palmerosa tributary.

The terrace has no preserved deposits associated with it, though in places remnant pockets of a mature calcrete are preserved that is at least stage 5 (after Machette, 1985). A further patch of terrace A is preserved at c.50m above the modern channel on the southern side of the stream upstream of the nickpoint developed at the head of the sub-reach (Figure 4.4.1).

4.4.2.2 Sedimentological Analysis

Less than 2m of sediment was preserved on the one remnant of terrace A therefore no sedimentological analyses could be performed. Within this reach the deposit does appear to be fully tractional in nature and clast size is generally c.2cm B axis.

4.4.3 Terrace B

4.4.3.1 The Terrace Record

Terrace B is preserved extremely patchily through the Argamason sub-reach and is preserved between 20 and 30m above the modern channel. The first remnants of terrace B are preserved immediately downstream of the nickpoint (Figure 4.4.1) and are c. 30m above the modern channel. The incisional base of the deposit is > 25m above the modern channel with < 2m of sediment preserved on the terrace surface. No calcrete development was noted through the area.

Terrace B is also preserved in the core of the abandoned meander associated with terraces C2 and D, downstream of Argamason village (X2 on Figure 4.4.1).The terrace surface is limited in spatial extent but cemented gravels can be seen having toppled down the hillslope following channel undercutting. The terrace surface is c.20m above the modern channel, and due to the nature of the collapsing blocks it is difficult to accurately determine the exact base of the incisional cut, but it lies somewhere between 15 and 20m above the channel.

Further downstream before the confluence with the Palmerosa tributary, a portion of the Carboneras Fault Zone is clearly picked out by the characteristic "painted" rocks associated regionally with the major fault zones. Above this feature is the last apparent remnant of terrace B, in this reach 15-20 m above the modern channel.

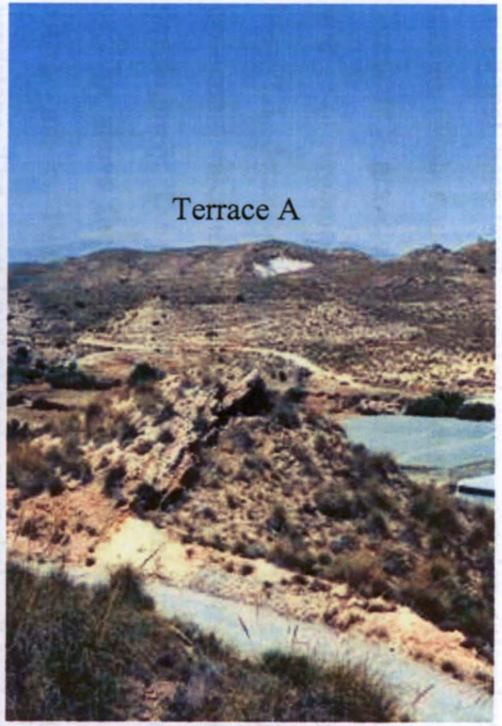


Figure 4.4.3. Terrace A preserved at the head of the basin directly over the Plio-Quaternary (?) anticline in the Cuevas Viejas Formation.

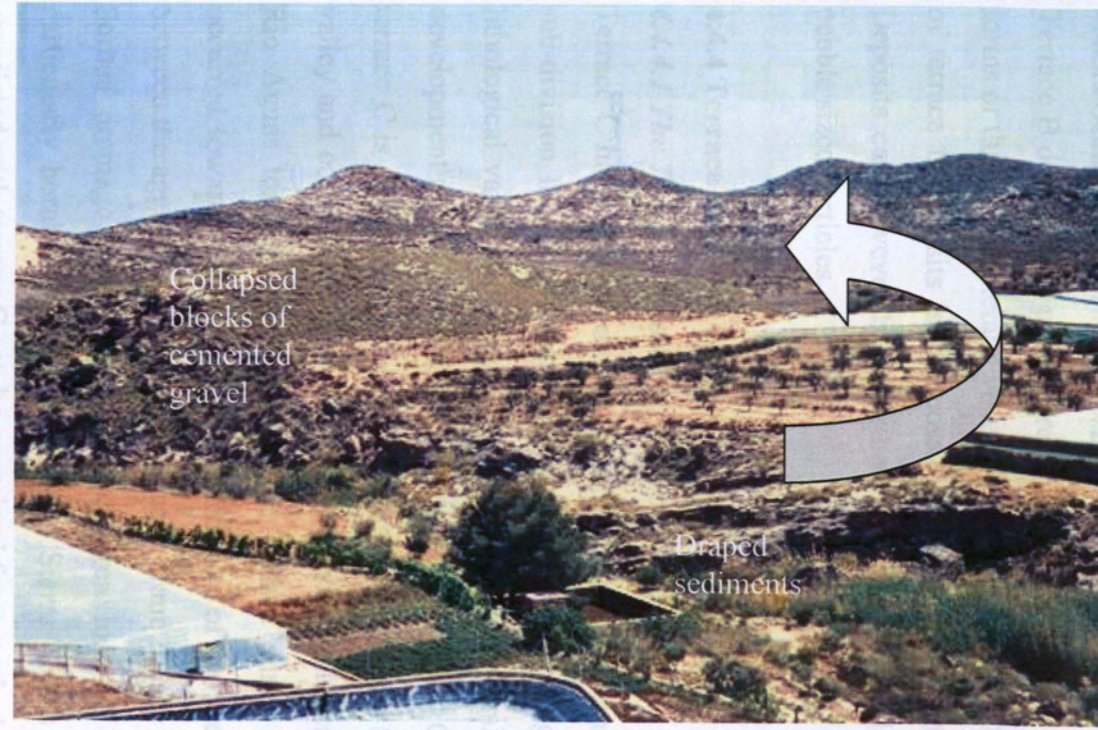


Figure 4.4.4. Abandoned meander of stage C2 indicated by greenhouses. In the foreground the draped sediments associated with the meander loop are evident. NB// At the core of the meander loop is a hill capped by terrace B sediments, with collapsed blocks on the hillslope below. Arrow indicates abandoned meander course.

4.4.3.2 Sedimentological Analysis

Terrace B deposits are poorly preserved throughout the Argamason sub-reach with strath forms or thin conglomeratic veneers (<3m) preserved. Detailed sedimentological analysis of terrace B deposits is not possible as no significant outcrop exposure is preserved. Deposits can however be described as coarse with clast size dominated by gravel to pebble sized particles.

4.4.4 Terrace C

4.4.4.1 The Terrace Record

Terrace C has been sub-divided in to C1 and C2 within the Argamason sub-reach. This sub-division has been created using the geomorphological assemblage alongside clast lithological variation to identify and sub-divide several possible phases of geomorphic development associated with ongoing tectonic activity. Clast lithological variation within terrace C is attributed to the river capture event in the Sorbas basin beheading the Feos valley and consequently the Rio Alias. Previous studies within the Sorbas basin on the Rio Aguas terrace sequence, and the current study, suggest that the capture event occurred towards the end of the aggradation of terrace C prior to the incisional event between the aggradation events of terraces C and D (see Chapter 7). The beheading of the Sorbas drainage resulted in a source area loss of high-grade metamorphic rocks, particularly hornblende schist, from the Sierra de los Filabres in the north. Deposits associated with terrace C can be examined for a marked decrease in the proportion of the characteristic hornblende Schist. Throughout the Argamason sub-reach terrace C can be defined by two phases marked by the proportion of hornblende schist and variations in incisional base-level, created by a complex interplay of climate, tectonics and river capture (Maher and Harvey, in press).

Terrace C1 gravels are preserved in only one location. The terrace surface on which the village of Argamason sits is capped by a thin veneer of C2 (?) sediments (<50cm) that bury C1 deposits directly underneath (Figure 4.4.5). The surface is capped by a pedogenic calcrete of approximately stage 3-4 (after Gile et al., 1966; Machette, 1985) development. The aggradational level of this unit, which may strictly relate to stage C2, is c. 20m above the modern channel. The base of the deposits underlying Argamason village are c. 10m+ above the modern channel cut into Cuevas Viejas formation sandstone. The exact level of incision is difficult to determine due to collapsed blocks of cemented gravel and a vegetated slope (Figure 4.4.6), however an outcrop of underlying bedrock allows a contact to be inferred. These terrace C deposits are characterised by a significant proportion of hornblende schist (see Chapter 5) and can therefore be assigned to the C1 sub-stage (i.e. prior to the capture). A strath associated with C1 is developed leading into the C age meander loop on which the village is situated (Figure 4.4.1/4.4.6) and is a continuation of the C1 strath developed above the upper nickpoint (Figure 4.4.3/4.4.7). This strath can be linked to the Gafares terrace assemblage.

The terrace/sediment assemblage becomes more complicated directly downstream of the village. Terrace preservation for each individual sub-stage is uncommon but sediment preservation is good. Cut into the C1 deposits, to a lower level, is a thick accumulation of well cemented gravels with an incisional base c.2-5m above the modern channel. Further downstream this incisional level descends closer to the level of the modern channel (Figure 4.4.6). The sediments are stratigraphically older than terrace D, and as there is no evidence of tectonic disturbance of terrace D here, have to be part of the overall C stage assemblage. Clast analysis (Chapter 5) of the deposits suggests the sediments belong to stage C2 as they contain only low amounts of hornblende schist. No soils are preserved on terrace C throughout this sub-reach and the dominant mode of cementation is via groundwater cementation, therefore allowing no relative age constraint of the deposits other than by clast analysis.

In the modern channel <30m further downstream (at Z on Figure 4.4.1), well cemented, indurated deposits outcrop on the channel bed (Figure 4.4.4/4.4.8). These deposits are clearly deformed exhibiting syn-sedimentary draping of the sediments down to the east, suggesting a normal (vertical) sense of movement along the fault. There is evidence for syn-and-post-depositional faulting (4.4.9) in this section, the effects of which will be discussed in section 4.6. The incisional base of the deposits is not seen throughout this section though a horizontal, conformable cap of cemented sediments is preserved at the top of the sequence (relating to the level of the abandoned meander at this location X2 on Figure 4.4.1) and is at c.15m above the modern channel (Figure 4.4.4). The clast assemblage alongside the geomorphological/sedimentological properties suggests that the sequence relates to terrace stage C2. The abandoned meander on the southern side of the river, though now buried by colluvial deposits of terrace D age also represents the course of the river at stages C1 and C2. No remnants of terrace C can be traced through the modern course until after the exit from the abandoned meander, but remnants of terrace C2 can be found at the entrance and exit of the abandoned valley system.

Figure 4.4.5. Terrace C1 deposits. Cross-bedded sands and gravels buried by a horizontal aggradational sequence, possibly of C2 age. NB// Stage 3-4 calcrete developed above persons head.

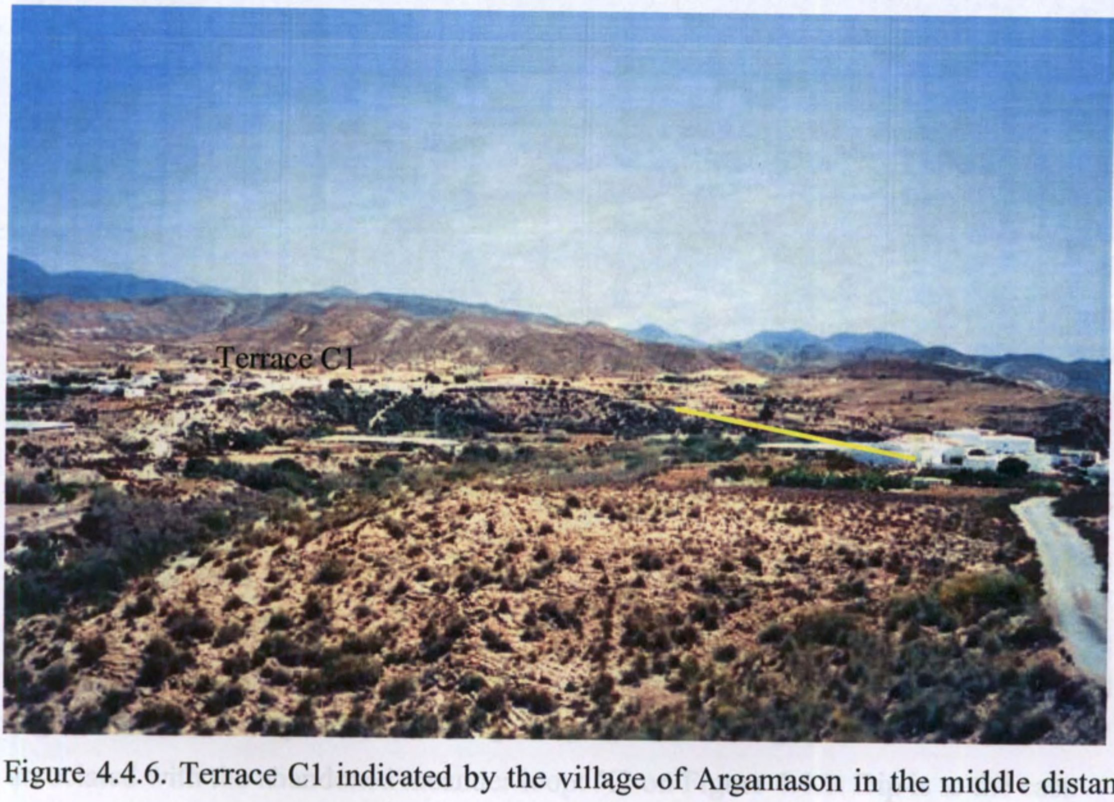


Figure 4.4.6. Terrace C1 indicated by the village of Argamason in the middle distance. Yellow line indicates the decreasing incisional level of the C2 deposits. Terrace D is below the village of Argamason. View is to the northeast.

Figure 4.4.7. Terrace assemblage in the area around the nickpoint. NB// Fold in background. View to the west.

Figure 4.4.8. C2 deposits exhibiting draping of bedding planes, the sediments are associated with the abandoned meander loop: X2 on Figure 4.4.1. Dip is to the east.

Figure 4.4.9. C2 deposits exhibiting evidence of post-depositional faulting. Bedding plane showing sub-vertical orientation behind person's head is in situ (X2: Figure 4.4.1).

Downstream of the abandoned meander, C2 deposits are preserved associated with an abandoned meander loop (X3 on Figure 4.4.1). A very small terrace surface is preserved on the southern side of the river c.10m above the modern channel exposing up to 10m of C2 sediments. The incisional base of the deposits cannot be seen as it is below the level of the modern channel. C2 deposits are preserved on the northern side of the stream on the outside of the third abandoned meander loop (X3 on Figure 4.4.1/4.4.10) and lie c.15-20m above the modern level of the main channel of the Rio Alias. An incisional level at the base of the deposits can be recorded here c.10m above the channel, relating to the valley side position prior to migration of the channel belt towards the south-east. Similar to other C age deposits the stratigraphic positioning of C2 was determined using several field properties including geomorphological mapping and positioning, stratigraphic relationships and the clast provenance signature. The C2 deposits here contain little or no hornblende schist and are cut into by local D age deposits. Furthermore, throughout the drainage basin of the Rio Alias the base of terrace D is not seen above the modern channel (the only exception is the Lucainena headwaters affected by local river capture) supporting the assignment of these sediments to stage C2. Downstream of this location only C2 sediments are preserved, and strath development is difficult to ascribe to a particular phase of development, but, given the height of the straths (c.15m) above the modern channel, C1 is most likely. Where C2 sediments are preserved the base is below the modern channel and is separated from terrace D by a difference in aggradational height above the modern channel and degree of cementation/induration of the deposits. C age deposits often show some degree of cementation and induration, whilst terrace D deposits do not show any consistency of cementation throughout a unit. The difference in the aggradational height of terrace C and D is c.5m, terrace C is preserved c.10-15m above the channel and terrace D preserved at c.7-10m.

4.4.4.2 Sedimentological Analysis

The amount of sedimentological analysis undertaken through the Argamason sub-reach varies due to outcrop preservation and location accessibility. Terrace C sediments are preserved throughout the sub-reach allowing analysis of the alluvial sediments associated with both terrace stages C1 and C2.

At the head of the sub-reach C2 sediments are preserved constrained within the nickpoint and heavily cemented by a groundwater calcrete (Figure 4.4.7). Structures are not discernable due to the penetration of the calcrete through the deposits. Clast size is consistent with that of a gravel bed system, gravels are the dominant grade preserved with cobbles and subordinate sand (Maher and Harvey, in press).

Analysis of the C1 deposit underlying Argamason village reveals a unit defined by lateral accretion surfaces associated with both individual bar-forms and channel fills (Figure 4.4.5). Channels are c.50cm-1m in apparent depth and vary from 2-3m in width to <1m where channels have been cross-cut by later erosional events. Foresets associated with the lateral accretion can be seen filling channel scours (Figure 4.4.5) then aggrading to form laterally accreting bars. Bar-form size ranges between 0.5 and 1m in height and c.2-3m in width. The size of the material varies from cobble to sand grade material with gravel deposits dominating the assemblage.

Overlying the lateral accretion deposits is a small unit c.0.5m in thickness associated with vertical aggradation of sheetflood deposits or longitudinal bars. There is a small, subtle erosive unconformity between the two deposits and the top of the uppermost unit is associated with the development of a stage III-IV pedogenic calcrete (Figure 4.4.5). Lithological analysis of the coarse component of the sediment assemblage (see chapter 5) implies that the uppermost sediments may be associated with stage C2 development of the terrace assemblage as there is a significant decrease in the proportion of hornblende schist.

C2 deposits preserved in the area of the modern road bridge (Figure 4.4.2/4.4.6) are inaccessible for anything more than provenance analysis. The deposit is, however, well cemented and indurated containing particles of sand-sized to cobble-sized material.

The deformed C2 sediments exposed in the modern channel (Figure 4.4.2/4.4.4) are a minimum of 7-8m in total thickness, however, accessibility and vertically consistent outcrop is limited to c. 4-5m. Sediments exposed on the northern side of the river are characterised by a coarse boulder bed at the base (partially submerged under the modern spring) overlain by a series of beds associated with both vertical and lateral accretion surfaces. The vertically accreting units are c.1-1.7m in height and beds within the deposit may pinch out laterally. Horizontal beds also appear to display some apparent concavity suggesting possible longitudinal bar development. Units between 1-2m thick are characteristic of lateral accretion deposits, these deposits are likely to be associated with laterally migrating bars as no channel structures were recorded. The foresets have a high angle of dip, >15°. The units are laterally persistent at >3m in width. The deposits are capped on the southern side of the stream by a horizontal layer of conglomerates at the level of the abandoned meander, the structures of which are not discernable.

Downstream, in the area adjacent to the exit point of the abandoned meander (Figure 4.4.1/4.4.11), a series of cemented fluvial conglomerates relating to stage C2 are preserved. Figure 4.4.11c displays a general section through the deposits and standard characteristics. Both lateral and vertical accretion surfaces are common. Channel structures are cut to a width of up to 4m and contain both lateral accretion surfaces and simple cut and fill vertical aggradation sequences, on a scale between c.0.8 and 1.5m in height. Horizontal beds of sand/gravel size material are likely to relate to sheetflood events as no other structures are discernable. Channels filled with lateral accretion surfaces represent channel migration with associated lateral point bars. The sequence is generally characterised by a series of stacked channels associated with lateral migration and sheetflood deposits.

C2 deposits are preserved on the outside of the second abandoned meander loop on the north side of the river (X2 on Figure 4.4.1/4.4.10). The deposits here are characterised by 2 distinct facies, the first a stack (>4m) of sand material relating to localised hillslope input from the volcanic bedrock (brought in by the fault) immediately surrounding the deposits. The deposits are generally massive, aggrading vertically, with sub-ordinate gravel horizons. Towards the modern channel across the abandoned valley the second facies is associated with coarse main river (?) gravels (Figure 4.4.12). An erosive unconformity with the underlying marl bedrock is revealed here due to the headwards incision of an aggressive modern tributary. The deposit is interpreted as representing the valley side of the meander bend before migration of the channel belt away towards the south, suggested by the terrace assemblage and the preservation of hillslope material behind.

The final remnants of terrace C preserved through the reach are adjacent to the modern confluence of the Palmerosa tributary (Figure 4.4.1). The deposits are heavily vegetated and exhibit a degree of cementation and induration not associated with D age sediments. No sedimentary analysis could be performed due to the poor nature of the outcrop. Clast analysis suggests the deposits are related to terrace stage C2 as the proportion of hornblende schist is c.1% (see chapter 5). Basic observations on the clastic material suggest a gravel bed river, with sub-ordinate boulder beds and sand layers.

4.4.5 Terrace D and E

4.4.5.1 The Terrace Record

Terrace D is preserved throughout the Argamason sub-reach both as strath forms and as aggradational terraces (Figure 4.4.1). The aggradational level of the terrace surface, or the height of the horizontal strath is between 7 and 10m throughout this portion of the system. Where the form preserved is a terrace with associated alluvium, the incisional base of the deposit is always below that of the modern channel. Downstream of the Palmerosa tributary the valley becomes confined by the resistant Cuevas Viejas formation and forms a canyon reach with limited depositional forms, only terraces and straths of C and D age preserved.

Only a small remnant of terrace D is preserved in the area around the nickpoint in the uppermost reaches of the sub-reach (Figure 4.4.1/4.4.7) c.7m above the modern channel. The main remnant of terrace D is below and downstream of Argamason village and no deposits have been identified. The issue may be one of preservation, however there is a significant possibility that the deposits have been simply covered by human dumping of waste associated with the plastic agriculture developed in the immediate vicinity. The abandoned meander developed on the southern side of the stream downstream of Argamason is buried by colluvial deposits post-dating the abandonment of the meander.

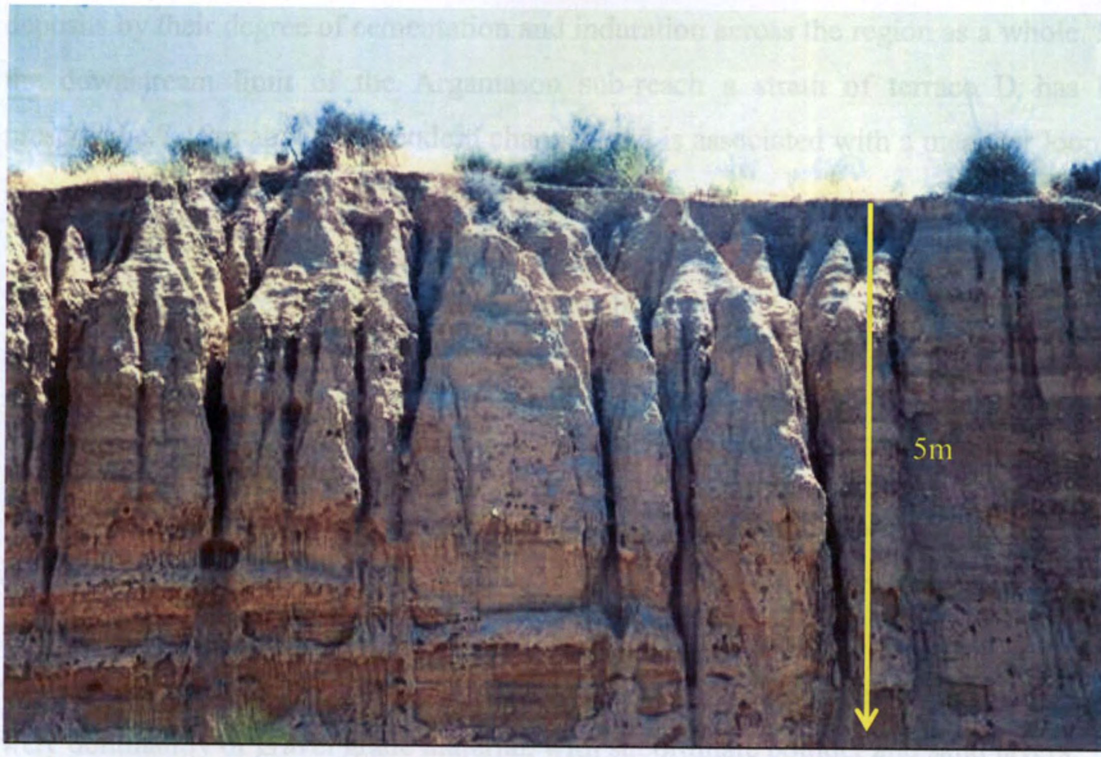


Figure 4.4.10. Fine hillslope derived sediments at the back of the abandoned C2 meander loop adjacent to the Rambla del Negro (X3 on Figure 4.4.1).

Towards the exit of the abandoned meander the development of a new tributary cutting through the uppermost deposits, has exposed some of the surficial deposits. No base can be seen to the deposits.

The second abandoned meander loop on the northern side of the stream (X3 on Figure 4.4.1) representing terrace stage C2, has an abandoned channel cut into it representing terrace stage D (Figure 4.4.13) of the tributary stream. The channel appears to have been cut-off by the headwards erosion of the modern tributary stream cutting back from the modern channel in a west-northwest direction (Figure 4.4.1), the reasons for which will be discussed in section 4.4.6. The abandoned channel is c.10m above the modern channel and has gravels preserved on the surface that have now been colonised and consequently covered by vegetation. Further D age sediments have been preserved in this location without any associated terrace surface and will be discussed in the next section.

Terrace D remnants are preserved adjacent to terrace C deposits just upstream of the Palmerosa tributary at c.7-m above the modern channel, the base of the incision is below the modern channel. Downstream of the Palmerosa tributary only two terrace remnants are preserved c.10m above the modern channel and as with the other terrace D deposits no incisional base can be observed. Terrace D deposits can be distinguished from C deposits by their degree of cementation and induration across the region as a whole. Near the downstream limit of the Argamason sub-reach a strath of terrace D has been preserved c.7-10m above the modern channel, and is associated with a meander loop that has progressively developed from terrace B times.

Terrace E is not preserved throughout this sub-reach at a scale that could be mapped consistently with the rest of the terrace features.

4.4.5.2 Sedimentological Analysis

Due to the nature of outcrop of terrace D sediments it has not been possible to do any detailed analysis of the deposits. As in other sub-reachs and for other terrace stages, general sedimentological characteristics were noted where possible. Throughout the reach the deposits were analysed for clast lithological properties (Chapter 5), and the deposits were dominantly of gravel grade material, with subordinate boulder and sand layers.

D age deposits associated with tributary development on the third abandoned meander loop (X3 on Figure 4.4.1/4.4.13), suggest soft sediment deformation along a subsidiary fault aligned in a north south direction picked out by an abnormally straight tributary channel (Figure 4.4.13). Foresets associated with bar accretion have an exceptionally high angle of rest that is unlikely to represent the true angle of deposition, and is more likely to have developed via draping and tilting due to normal movement along a fault plane. This area of deformation co-incides with the recent (Holocene) development of the aggressive tributary that has cut-off the arcuate D-age channel developed within the C2 terrace surface of the abandoned meander.

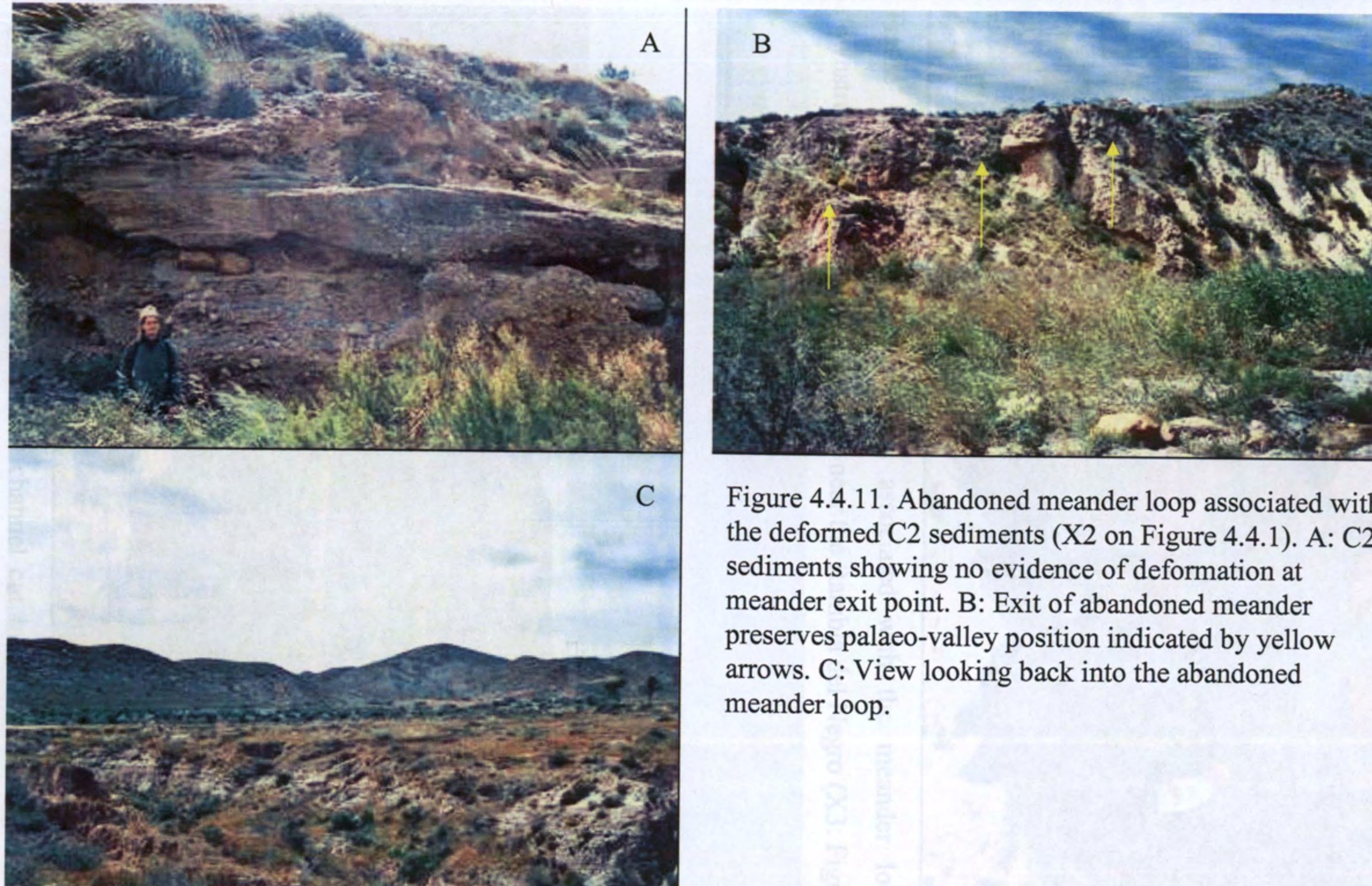


Figure 4.4.11. Abandoned meander loop associated with the deformed C2 sediments (X2 on Figure 4.4.1). A: C2 sediments showing no evidence of deformation at meander exit point. B: Exit of abandoned meander preserves palaeo-valley position indicated by yellow arrows. C: View looking back into the abandoned meander loop.

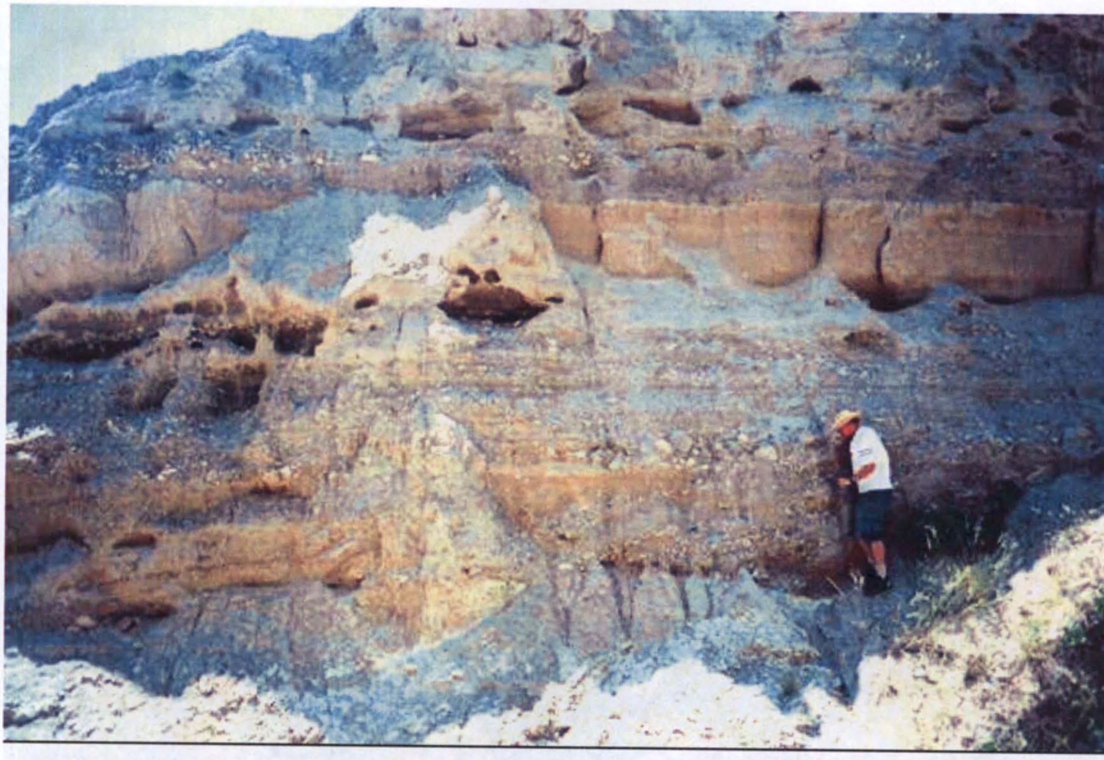


Figure 4.4.12. Terrace C2 deposits associated with the meander loop developed downstream of the zone of defomation near the Rambla del Negro (X3: Figure 4.4.1).

Figure 4.4.13a. Abandoned terrace D channel cut into terrace C2 (X3: Figure 4.4.1). View to the northwest.

Figure 4.4.13b. Faulted D age sediments associated with the Rambla del Negro. High angle of dip associated with foreset development, downdrop on the fault to the east (movement indicated by arrow). NB// the disrupted bedrock material.

4.4.6 Palaeo-environmental Synthesis

4.4.6.1 Terrace A

Terrace A is poorly preserved across the Argamason sub-reach. It is impossible to ascertain whether this is due to post-depositional removal of the sediment, or, to the fact that this part of the system was highly erosional even during climatically driven aggradational phases due to base-level lowering via the Carboneras Fault Zone. Sediments are so limited that only an inference can be made regarding the nature of the river in terms of the material it can transport. Stream power appears to have been similar to today with gravel and pebbles the dominant grade of transported material.

Terrace A is preserved at slightly higher levels in this sub-reach than most other terrace A remnants through the Alias system. There are two possible and likely reasons for this occurrence: the first is tectonically induced uplift of the areas associated with terrace A. The preserved strath of terrace A (Figure 4.4.1/4.4.3) is sitting on top of the large anticline developed within the Neogene basin fill. This structure also controls the development of the large nickpoint which consequently prevented the upstream migration of the effects of tectonic base-level change at Argamason (Maher and Harvey, in press). It is likely the development of the structure is related to the activity on the main fault zone, taking up stresses created by the early lateral movement along the fault. Consequently, with continued Quaternary movement along the fault and the development of the nickpoint during terrace C times, it is likely that this structure has experienced some movement during the development of the modern river system.

The second possible cause of the raised level of terrace A is increased headwards incision towards the head of the basin caused by tectonic lowering of base-level in the area around and downstream of Argamason. Tectonic lowering of base-level during and post terrace C times has been inferred from the assemblage of sediments in the area adjacent to the fault zone. However, the lack of preserved A and B age deposits throughout the sub-reach makes it difficult to definitively identify any earlier tectonic movement, though the geomorphic assemblage or rather lack of it, may suggest such movement. Continued tectonic activity during the early evolution of the Quaternary system is likely and Keller et al. (1995) suggest that it was mainly by vertical motion. Given continued, pulsed vertical movement along the fault, local base-level would have been lowered. This would have increased the river gradient and local stream power which would have encouraged lateral migration of the channel belt and increased headwards incision. Consequently the amount of incision following the deposition of terrace A may have increased through this portion of the system relative to that in any of the upstream sub-reachs.

The poor preservation of Terrace A and any associated deposits makes it difficult to constrain the behaviour of the fluvial system in this period. However, detailed geomorphological mapping and sedimentological analysis of younger deposits allows some idea of how tectonics may have affected the evolution of this portion of the system at terrace A times. It seems most likely that the two prior mentioned tectonic forcings combined to control the evolution of the system during terrace A times and determine the assemblage preserved today.

4.4.6.2 Terrace B

Terrace B is preserved in a similar manner to terrace A. Remnants are patchy and associated with only thin veneers of sediment, excluding the collapsed cemented blocks of terrace B. The terrace remnants do not preserve enough sediment to reveal information regarding fluvial processes, but the aggradational heights of the terrace and the levels of incision prior to aggradation do yield important information regarding the evolution of the system during terrace B times.

Figure 4.4.2 shows the long profile of the terrace assemblage through the Argamason sub-reach, and it highlights the nature of the decreasing aggradational and incisional level of terrace B decreasing down-system. There are two likely causes for this manifestation: the first is a tectonic lowering of base-level causing the incisional phase to progressively incise below the level of the upstream channel and consequently aggrade to a slightly lower level than upstream. The overall base-level drop would have to be downstream of the terrace B remnant developed over the axis of the fault zone picked out by the fault rocks. This model is consistent with down-drop on the southeast side of the fault zone. The suggestion of down-drop on the southern side of the fault is further supported by the apparent movement on the individual subsidiary faults deforming terrace C and possibly D sediments throughout this reach.

A second possible mechanism of development is associated with a gradual downstream progression towards the distal limit of the sub-reach defined by the canyon reach and the lower nickpoint. As river systems progress towards their distal reaches terraces tend to merge towards a constant base-level. The base-level to the Argamason sub-reach is the downstream nickpoint (NP2 on Figure 4.4.1) developed in resistant Cuevas Viejas sandstone at the distal end of the canyon developed in the same lithological unit. Both structures would limit the behaviour of the upstream and downstream sections of the system. This nickpoint is likely to mark the limit of the upstream propagation of any eustatic variations in base-level, thus defining the final sub-reach at the seaward end of the system (to be discussed in section 4.5). The nickpoint and the canyon acting as a base-level control could possibly cause the upstream terraces to pinch toward this area. This however, is unlikely as the younger terrace units do not appear to exhibit this same control towards the sub-reach margin.

The decrease in the level of terrace B throughout this reach and the absence of preserved terraces as a whole are likely to reflect changing base-levels on the south-eastern side of the fault zone. The downstream propagation of the base-level drop is difficult to determine due to the development of the canyon reach and the sub-reach margin. Furthermore, it can be suggested that the drop in base-level increased the amount of incision during both the incisional event preceding terrace B. Consequently inhibiting deposition on the aggradation phase and increasing the removal of sediment during the subsequent incisional phase would lead to very little preservation of terrace B deposits.

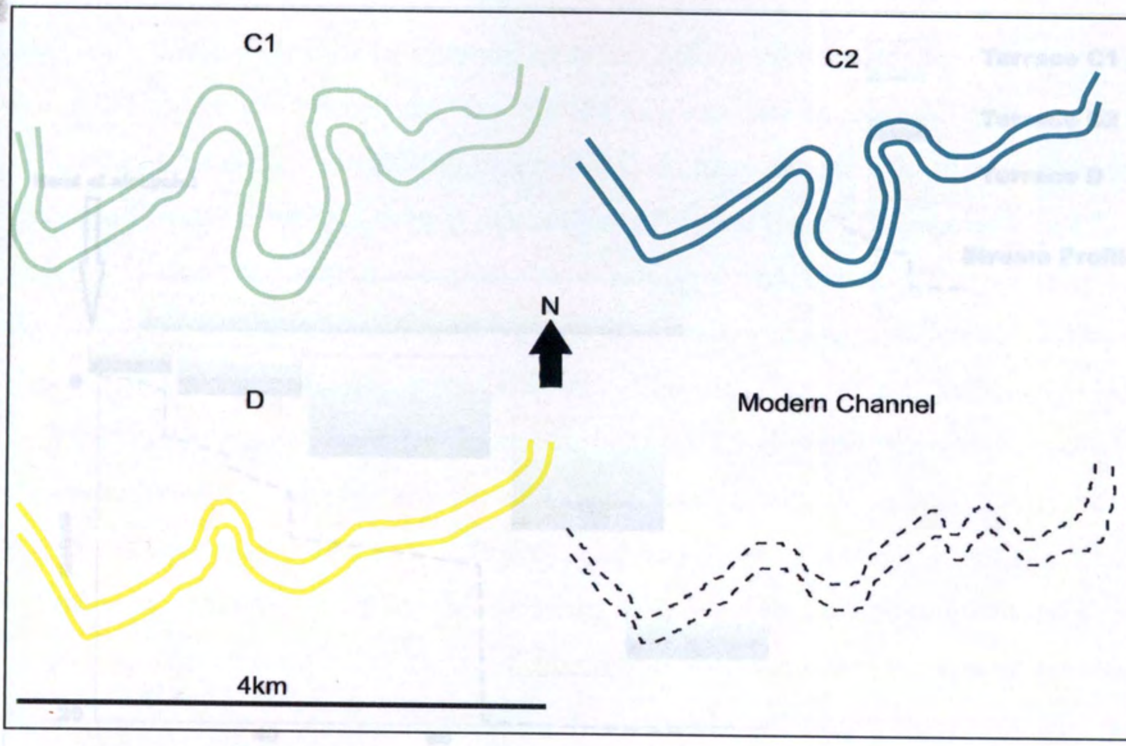


Figure 4.4.14a. Planform development of channel through the zone of tectonic deformation. Taken from Maher and Harvey (in press).

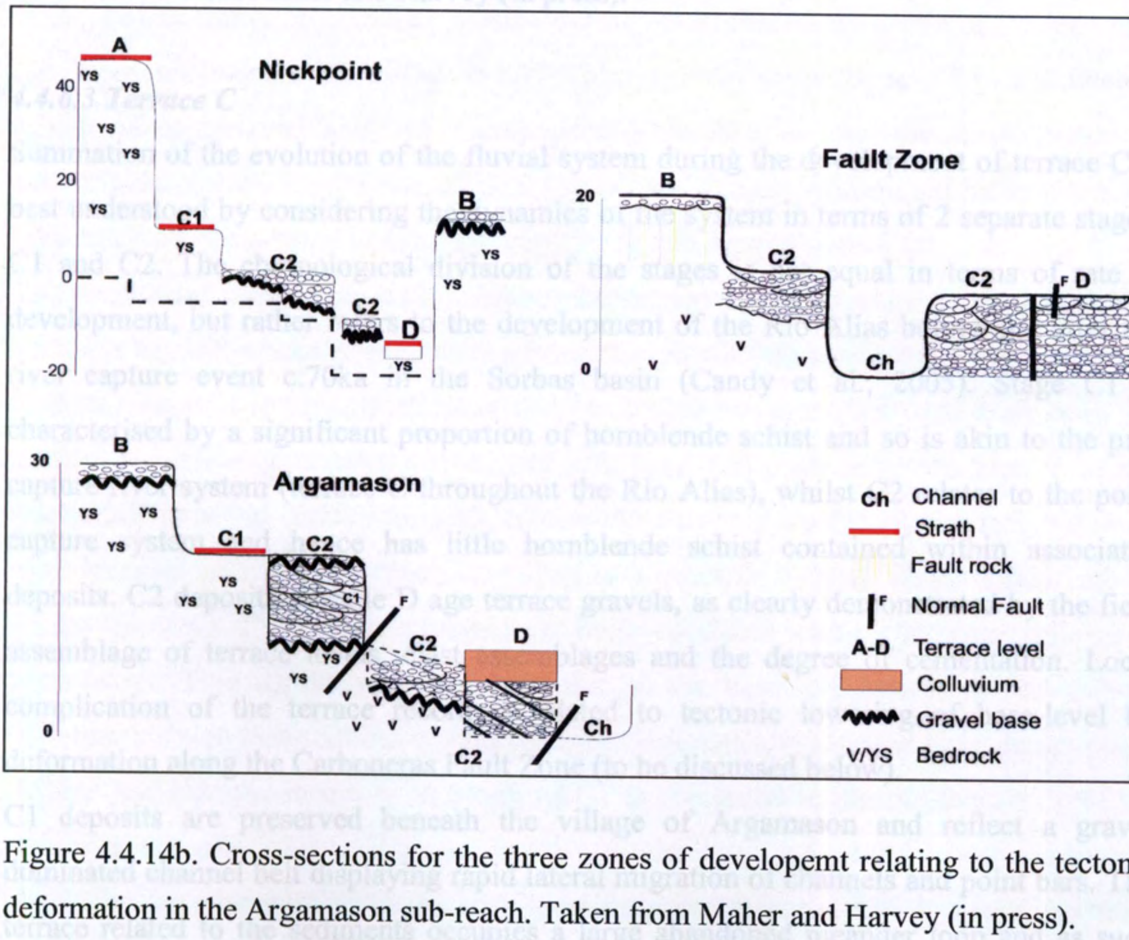


Figure 4.4.14b. Cross-sections for the three zones of developemt relating to the tectonic deformation in the Argamason sub-reach. Taken from Maher and Harvey (in press).

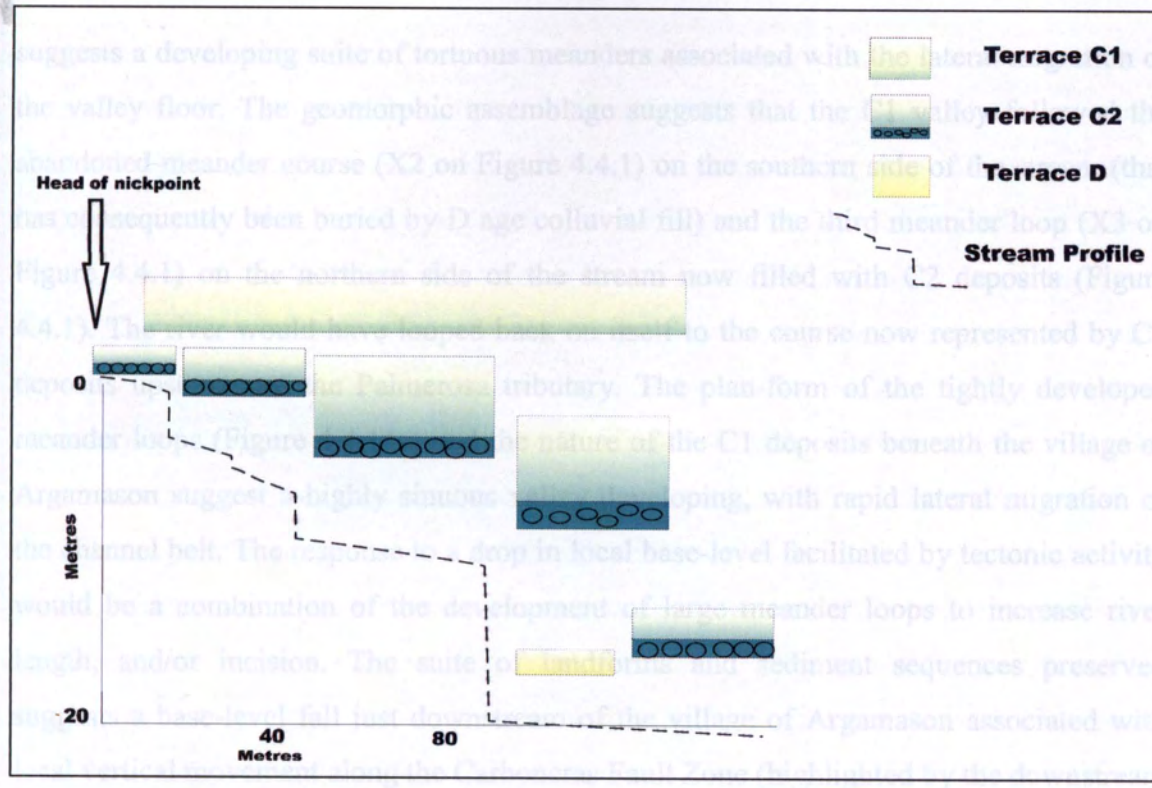


Figure 4.4.15. Long-profile of the nickpoint developed at the head of the Argamason sub-reach. Taken from Maher and Harvey (in press).

4.4.6.3 Terrace C

Summation of the evolution of the fluvial system during the development of terrace C is best understood by considering the dynamics of the system in terms of 2 separate stages; C1 and C2. The chronological division of the stages is not equal in terms of rate of development, but rather refers to the development of the Rio Alias before and after the river capture event c.70ka in the Sorbas basin (Candy et al., 2005). Stage C1 is characterised by a significant proportion of hornblende schist and so is akin to the pre-capture river system (terrace C throughout the Rio Alias), whilst C2 relates to the post-capture system and hence has little hornblende schist contained within associated deposits. C2 deposits precede D age terrace gravels, as clearly demonstrated by the field assemblage of terrace levels, clast assemblages and the degree of cementation. Local complication of the terrace record is related to tectonic lowering of base-level by deformation along the Carboneras Fault Zone (to be discussed below).

C1 deposits are preserved beneath the village of Argamason and reflect a gravel dominated channel belt displaying rapid lateral migration of channels and point bars. The terrace related to the sediments occupies a large abandoned meander loop and as such suggests a developing suite of tortuous meanders associated with the lateral migration of the valley floor. The geomorphic assemblage suggests that the C1 valley followed the abandoned meander course (X2 on Figure 4.4.1) on the southern side of the stream (that has consequently been buried by D age colluvial fill) and the third meander loop (X3 on Figure 4.4.1) on the northern side of the stream now filled with C2 deposits (Figure 4.4.1). The river would have looped back on itself to the course now represented by C2 deposits upstream of the Palmerosa tributary. The plan-form of the tightly developed meander loops (Figure 4.4.14a) and the nature of the C1 deposits beneath the village of Argamason suggest a highly sinuous valley developing, with rapid lateral migration of the channel belt. The response to a drop in local base-level facilitated by tectonic activity would be a combination of the development of large meander loops to increase river length, and/or incision. The suite of landforms and sediment sequences preserved suggests a base-level fall just downstream of the village of Argamason associated with local vertical movement along the Carboneras Fault Zone (highlighted by the downstream variation in cross-section: Figure 4.4.14b). The lack of preservation of C1 sediments and landforms downstream of this section makes it difficult to ascertain the occurrence or timing of any tectonically driven incision during the aggradational phase of C1. The base of C1 deposits beneath the village is c.10m above the modern channel. The inference of this geomorphological and sedimentological assemblage is that the tectonic activity affecting the evolution of terrace stage C1 may have occurred during the incisional event prior to aggradation but at the latest during the aggradation of terrace C1.

C2 deposits are well preserved throughout the Argamason sub-reach; the most upstream remnants are at the head of the sub-reach, associated with the modern day nickpoint. The modern nickpoint is cut into resistant Cuevas Viejas sandstone and into a groundwater cemented calcrete associated with terrace C2. No C1 deposit has been located at this location. This could be due to post-depositional stripping caused by the tectonic base-level lowering of C2 downstream encouraging headwards incision. Alternatively, phase C1 development at the nickpoint may have been associated with incision and little or no aggradation. This would be conceivable due to the base-level lowering downstream initiating incision that could overcome a regional climatically-induced aggradation phase (Maher and Harvey, in press). A strath of C1 is preserved on the southern side of the stream at the nickpoint, as an abandoned meander loop suggesting a tortuous course developed here in reaction to the base-level drop downstream. The increase in stream length compensating for the increase in gradient, would not be of sufficient proportions to inhibit its incision down to the base of the C2 deposits in this location. The erosional base of the C2 deposits at the modern nickpoint suggests that a nickpoint was initially formed during the incisional event associated with stage C2 (Figure 4.4.15). It is therefore likely that the incision wave associated with the base-level fall in the area around Argamason village was held up by the development of the nickpoint (Maher and Harvey, in press). Upstream of the nickpoint there is no suggestion of lateral migration or incision associated with a base-level fall downstream, consequently the impact of a base-level fall of c.5m at Argamason has propagated only c.1km upstream. Furthermore, the nickpoint development was initiated by the headwards propagation of the incision wave caused by the tectonic lowering of base-level around the village of Argamason. This nickpoint was then buried on the aggradational phase associated with stage C2, and has since been exhumed by the modern wave of incision. The limited preservation of D age terraces and straths also suggest that the nick point was exhumed again on the incisional event preceding D aggradation and consequently buried by the aggradation of terrace D (Maher and Harvey, in press).

In the area immediately surrounding Argamason village, the preserved suite of terraces and gravel deposits record a complicated history of evolution during C1, C2 and D times. C2 (?) deposits form a thin veneer (c.50cm) on the C1 deposits underlying Argamason village, the base of the deposits, lying disconformably on C1 deposits, is around 20m above the channel. Less than 100m downstream, C2 deposits (with no associated terrace preservation) are preserved with an erosional base decreasing from c.5m above the modern channel to 2m above the channel, and finally to below the level of the modern channel (Figure 4.4.2). C2 deposits exhibit syn-sedimentary deformation in this location with draping of the sediments visible (Figure 4.4.8). The assemblage of C2 deposits suggests ongoing tectonic deformation during deposition of the sediments. The large vertical difference in relief of the C2 deposits overlying C1, and the deformed sediments in the channel (>20m) also indicate some post-depositional faulting along one of the subsidiary faults in the area (see Figure 4.4.1). It is difficult to ascertain any definite fault plane as younger sediments and vegetation cover much of the exposure, but the pronounced variation in the level of the base of the C2 deposits is unlikely to reflect the level of actual deposition. Downstream of the major zone of late-Quaternary tectonic disturbance the C2 deposits dominate, the base of which is below that of the modern stream level. However no tectonic disturbance is discernable suggesting the tectonic movement was limited to the area immediately downstream of the village of Argamason (a zone around 100m in width).

The planform expression of the channel during C2 aggradation (Figure 4.4.14a) shows lower sinuosity from that of C1, as meanders were cut-off during the incisional event driven by the local base-level fall. This suggests that following the fall in local base-level the river system first responded to the increase in gradient by developing a tortuous meander belt. However, a threshold was crossed and the increase in stream length was not sufficient to compensate for the tectonic base-level lowering, so incision ensued before the climatically driven regional phase of aggradation was re-established (i.e. C2 aggradation). During the aggradation of terrace C2 the channel belt continued to developed tight meander loops following a similar pattern to that of terrace C1, probably related to the increase in gradient caused by the apparent pulsed vertical movement along local faults (reflected in the C2 deformed sediments).

4.4.6.4 Terrace D

Following the aggradation of terrace C2 a phase of incision led to the cut-off of many of the meander loops and the development of a channel configuration similar to that of the modern stream (Figure 4.4.14a). This incision is thought to relate to a regional climatically generated control, however, local base-level lowering due to tectonic movement along established fault lines may have exacerbated this incision (see section 4.4.5.2). At the head of this sub-reach erosion appears to dominate even the development of terrace D. The landforms preserved are erosional straths suggesting that development through this portion of the system may have been wholly incisional during terrace D times. This is consistent with the development of an incision wave passing up the system in response to a local base-level lowering at Argamason. The incision wave appears to have been of sufficient size to have overcome the regional pattern of increased sediment supply that lead to terrace aggradation.

In the area surrounding the village of Argamason terrace D is well developed and is fairly continuous downstream. Colluvial deposits equivalent to terrace D age bury older C1 deposits in the floor of the meander loop (X2 on Figure 4.4.1) implying the loop had been abandoned prior to the aggradation of terrace D. Terrace D deposits are preserved downstream of the exit point of the large abandoned meander (X2 on Figure 4.4.1). The terrace sequence from C to D exhibits gradual lateral migration of the channel belt downstream of the zone of intense tectonic activity rather than rapid abandonment of

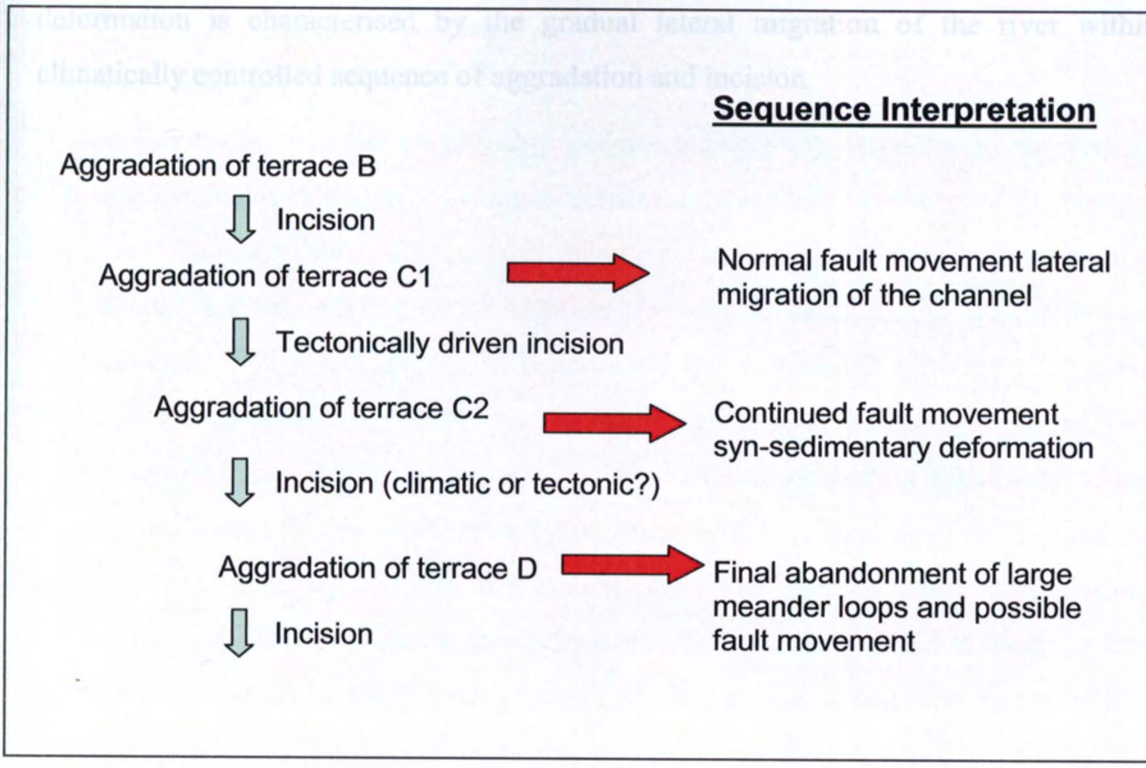


Table 4.4.2. General sequence interpretation for the Argamason sub-reach (taken from Maher and Harvey, in press).

meander bends. This further implies that the terrace assemblage and fluvial behaviour in the area around Argamason and upstream was driven dominantly by tectonic deformation causing the development of tortuous bends followed by rapid incision and cut-off.

The terrace sequence within the Argamason sub-reach reflects the complex interplay between regional climatically generated patterns of aggradation and incision, and local tectonic modifications. Table 4.4.2 summarises the general sequence of events in terms of climatic and tectonic pulses and the resultant effect on the fluvial system. The effect of this activity varies depending on the proximity to the zone of deformation. It is clear that within the zone immediately downstream of Argamason village, where the tectonic deformation was concentrated, the fluvial system reacted in several different ways. Firstly large meanders developed as a response to the increase in gradient and when this was not sufficient to lower the gradient, incision ensued. Within this zone syn-sedimentary deformation is also apparent. 1km upstream of this zone the system response was dominated by incision and the development of a nickpoint in adjustment to the downstream base-level change. And finally the zone downstream of the intense deformation is characterised by the gradual lateral migration of the river within a climatically controlled sequence of aggradation and incision.

4.5 The El Saltador Sub-Reach

4.5.1 Introduction

The westwards limit of the El Saltador sub-reach along the Rio Alias, is defined by a lower nickpoint developed in the Cuevas Viejas sandstone just northwest of the village of Llano don Antonio (GR: 5941 40962, Sheet no. 1031-IV) and the headwaters of the Rambla del Saltador (GR: c.5919 41003). The eastern limit of the sub-reach is the Mediterranean Sea (5998 40983). Upstream of the confluence with the Rambla del Saltador the Rio Alias is confined by a canyon, 1km in length cut through Cuevas Viejas sandstone. The Rambla del Saltador is a large tributary draining the Sierra Cabrera flowing transverse to the Carboneras Fault Zone, which is developed to its maximum width (c.1km) in this portion of the system. The final coastal stretch of the modern channel of the Rio Alias is characterised by a broad channel belt with few meander loops. Terrace preservation is fairly poor throughout this area and sediment preservation is extremely patchy. Pedogenic carbonate development is limited to only 3 clear sites whilst no soil has been preserved overlying any terraces throughout the sub-reach.

Terrace	Height of Terrace Surface	Incisional Level	Calcrete Development	Soil RI	Cementation/ Induration
A	40-45m	30-35m	4-5	NA	Cemented and indurated
B	35-15m	25-0m	4-5	NA	Cemented and indurated
C	20-10m	10-0m	3	7.5	Cemented some induration
D	10-5m	*	0	NA	Loose sediment
E	5-0m	*	0	NA	Loose sediment

Table 4.5.1. Terrace characteristics for the El Saltador sub-reach. NA=no soil preserved. *= base below modern channel. Calcrete development after Gile et al., (1966) and Machette (1985).

4.5.2 Terrace A

4.5.2.1 The Terrace Record

Terrace A is preserved in only two areas within the El Saltador sub-reach (Figure 4.5.1). The first terrace remnant is located near to the village of Llano don Antonio where the

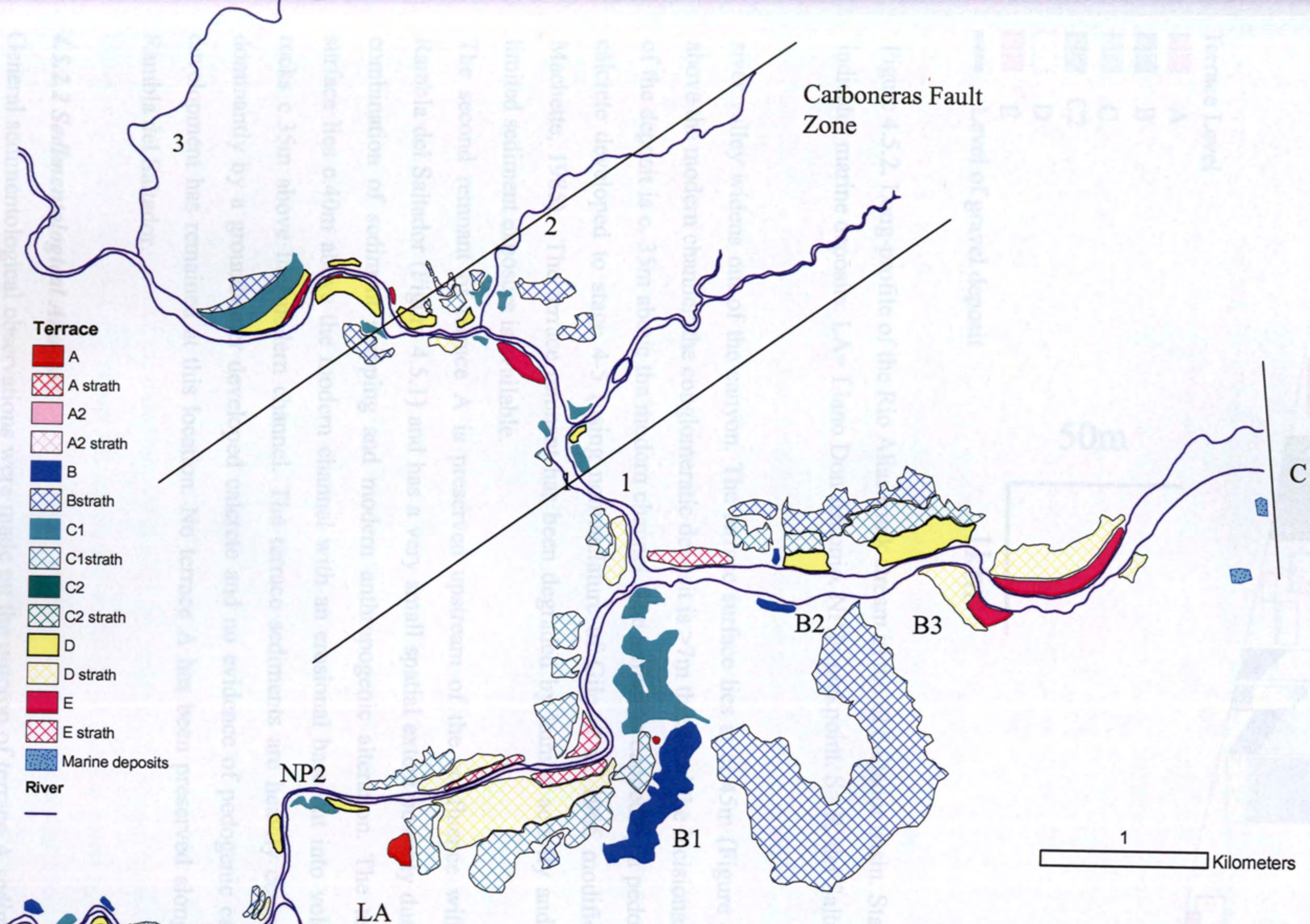


Figure 4.5.1. Terrace map of the El Saltador sub-reach.. 1) Rambla del Saltador. 2) Barranco del Arto. 3) Rambla del Garcia. LA= Village of Llano don Antonio. C= Coast. B1/B2/B3 refer to text. NP2=Nickpoint upstream of L.D. antonio.

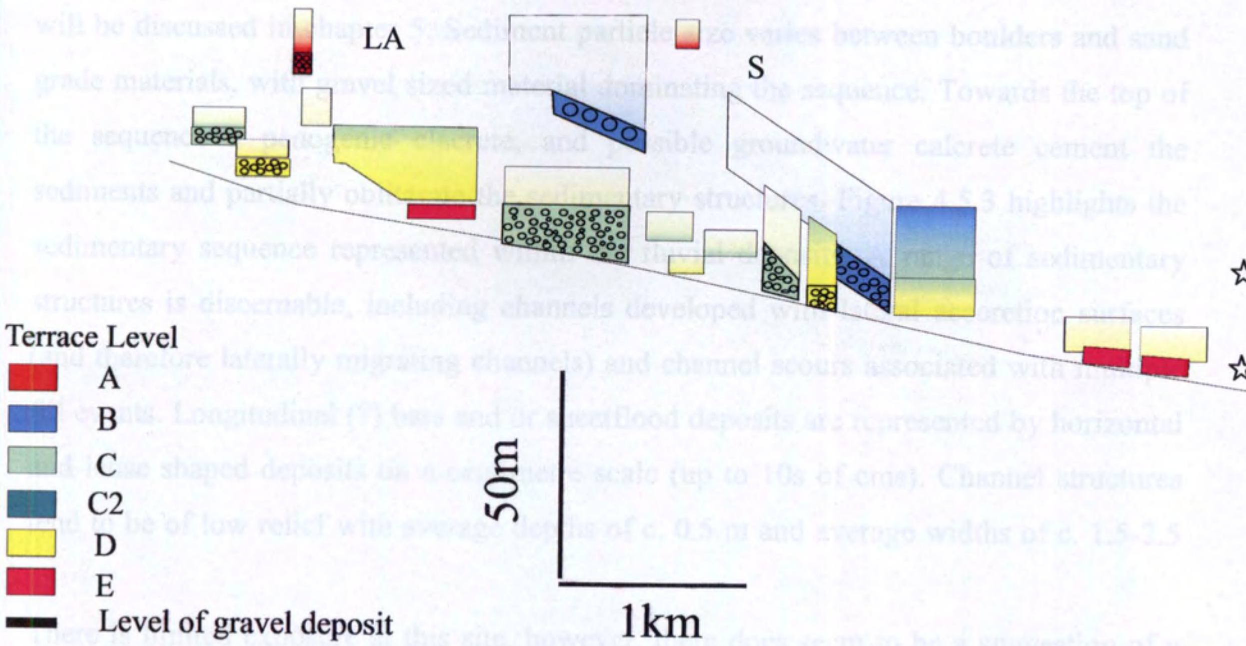


Figure 4.5.2. Long-profile of the Rio Alias trunk stream in the El Saltador basin. Star indicates marine deposits. LA= Llano Don Antonio. NP2= nickpoint. S= R. del Saltador.

river valley widens out of the canyon. The terrace surface lies at c. 45m (Figure 4.5.2) above the modern channel; the conglomeratic deposit is >7m thick and the incisional base of the deposit is c. 35m above the modern channel. The terrace is capped by a pedogenic calcrete developed to stage 4-5 (using nomenclature of Gile et al. 1966 modified by Machette, 1985). The terrace remnant has been degraded by human activity and only limited sediment exposure is available.

The second remnant of terrace A is preserved upstream of the confluence with the Rambla del Saltador (Figure 4.5.1) and has a very small spatial extent possibly due to a combination of sediment stripping and modern anthropogenic alteration. The terrace surface lies c.40m above the modern channel with an erosional base cut into volcanic rocks c.35m above the modern channel. The terrace sediments are heavily cemented, dominantly by a groundwater developed calcrete and no evidence of pedogenic calrete development has remained at this location. No terrace A has been preserved along the Rambla del Saltador.

4.5.2.2 Sedimentological Analysis

General sedimentological observations were made on the outcrop of terrace A sediments near the village of Llano don Antonio (Figure 4.5.1). Clast lithological and shape data will be discussed in chapter 5. Sediment particle size varies between boulders and sand grade materials, with gravel sized material dominating the sequence. Towards the top of the sequence a pedogenic clacrete, and possible groundwater calcrete cement the sediments and partially obliterate the sedimentary structures. Figure 4.5.3 highlights the sedimentary sequence represented within the fluvial deposits. A range of sedimentary structures is discernable, including channels developed with lateral acceretion surfaces (and therefore laterally migrating channels) and channel scours associated with multiple fill events. Longitudinal (?) bars and or sheetflood deposits are represented by horizontal and lense shaped deposits on a centimetre scale (up to 10s of cms). Channel structures tend to be of low relief with average depths of c. 0.5 m and average widths of c. 1.5-2.5 m.

There is limited exposure at this site, however, there does seem to be a suggestion of a transition from sheetflood dominated deposits at the base of the sequence to more channelised deposits at the top of the sequence. Within the sheetflood deposits there is a suggestion of fining-up within the units indicating deposition of each set by one flood. The channelised deposits are characterised by perpendicular foreset development (i.e. lateral accretion of bars), and by multiple fining-up sequences. The erosional horizon associated with the multiple event fill is not always a clear channel structure, with broad shallow erosional horizons also associated with the multiple aggradational fill sequences.

4.5.3 Terrace B

4.5.3.1 The Terrace Record

Terrace B is best preserved in the coastal portion of the Rio Alias. Both erosional strath forms and terraces associated with conglomerate deposits are preserved along both the Rio Alias and the Rambla del Saltador tributary stream (Figure 4.5.1/4.5.2). Terrace B is preserved as a series of large abandoned meander loops predominantly on the southern side of the river channel (Figure 4.5.1). The terrace height is c. 30m above the modern channel and has a preserved calcrete of around stage 4. The incisional base of the terrace deposits decreases substantially in a downstream direction (Figure 4.5.2) from c.25m on the outside of the abandoned meander loop on the southern side of the stream (denoted by B1 on Fig. 4.5.1) to c.3m and below the modern channel in the area de-noted by B2 on Figure 4.5.2. This is an extremely steep gradient developed on the incisional event prior to the aggradation of terrace B. The meander loop (Figure 4.5.4) continues to the north side of the modern channel forming an extremely tight meander loop. The terrace surface on the northern side of the channel is c.20m above the

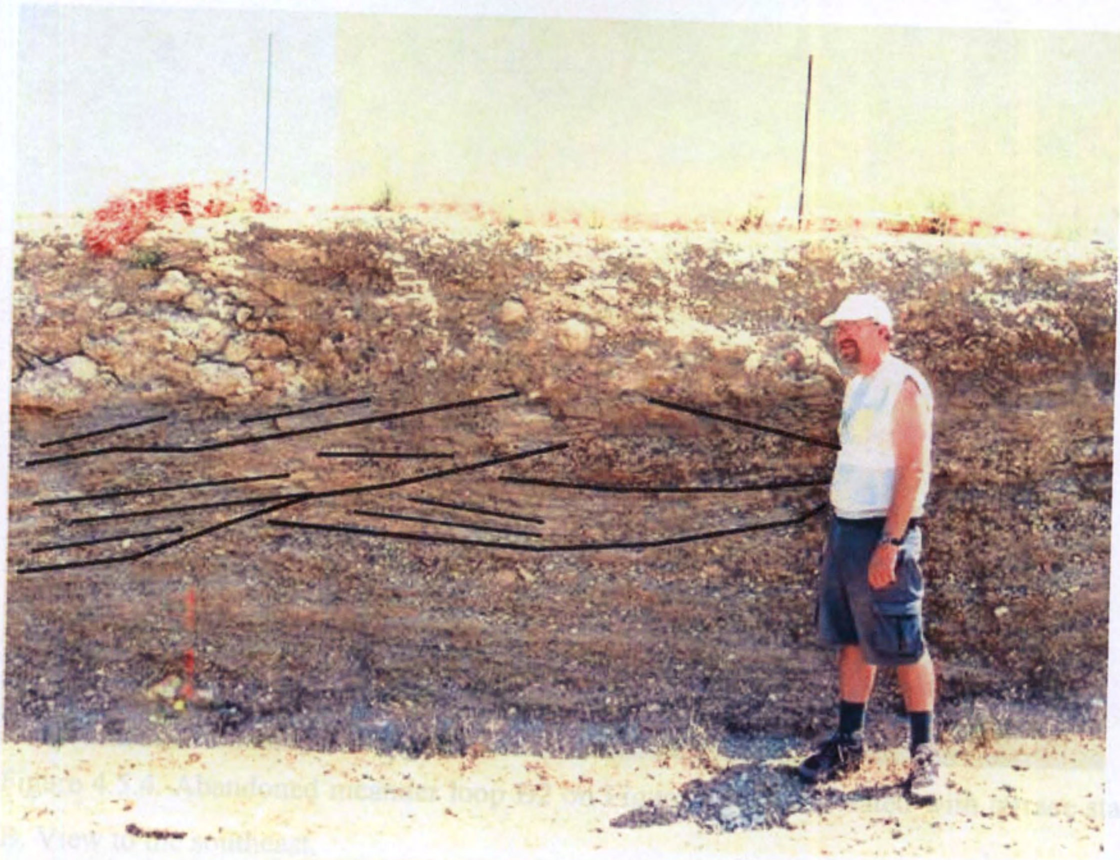


Figure 4.5.3 a/b. Terrace A sediments preserved at Llano don Antonio. Sketch B is taken from the base of the sequence and is dominated by sheetflood deposits, and presence of floating clasts suggests hyper-concentrated flow. Up-sequence channelised deposits are

visible. Sketch A is the top of the sequence and channelised deposits with laterally accreting bars dominate the sequence. Person is 1.85m.

Figure 4.5.4. Abandoned meander loop B2 on Figure 4.5.1, associated with terrace stage B. View to the southeast.

Figure 4.5.5. Terrace B sediments on the north side of the modern river valley. Palaeo-valley margin is preserved (arrows) cut into volcanic bedrock.

modern channel and a thick gravel sequence is preserved indicating the original position of the main channel belt and the valley side at terrace stage B (Figure 4.5.5). The base of the gravels in what would have been the centre of the channel belt is below the level of the modern channel.

Downstream of this well developed meander belt of terrace B there is no further preservation of terrace B as a terrace surface or erosional strath. There is however a stack of well cemented fluvial deposits preserved (denoted as B3 on Figure 4.5.1) that are consistent with B age deposits through this reach. They are not associated with a terrace surface but are cut by an erosional strath across the deposits, developed during terrace D times (Figure 4.5.6). At the upstream portion of the reach no B sediments are preserved, but the B course may have followed the abandoned loop developed to the south of the modern channel.

4.5.3.2 Sedimentological Analysis

Terrace B deposits are most easily accessible and best preserved at a section cut obliquely by the modern channel in the area of the large meander loop exit (B2 on Figure 4.5.1/4.5.4b). Figure 4.5.7 is a sketch log of a c. 5m section through the cemented deposits characteristic of gravel associated with terrace B. The unit is dominated by a series of stacked channels associated with both vertical fill sequences and foreset development oblique to channel structure indicating point bar development. Clast analysis will be discussed in the next chapter in detail, but the general particle size distribution ranges from sand grade material to cobbles. There is no preservation of boulder sized material at this location.

Channel structures are generally c.1m in depth and 1-3m in width at the base of the section. A unit of lateral accretion surfaces (foreset development with oblique clast imbrication) is preserved at the base of the section with a preserved depth of c.1m. Towards the top of the sequence there is a large channelised unit with a depth of c.2m and width of c.4.5m, containing planar cross bedded sands and gravels. The general sequence preserved within these terrace B deposits is characteristic of a braided river environment. Terrace B deposits preserved further upstream, on the outside of the palaeo-meander bend (B1 on Figure 4.5.1) are of a limited spatial extent and outcrop is extremely limited preventing any detailed sedimentary analysis of the deposit. General observations do confirm the fully tractional nature of the deposit (i.e. clast supported) and a dominance of gravel sized material with sub-ordinate sand and cobbles.

Figure 4.5.6. B age cemented fluvial gravels cut into by a strath associated with stage D.

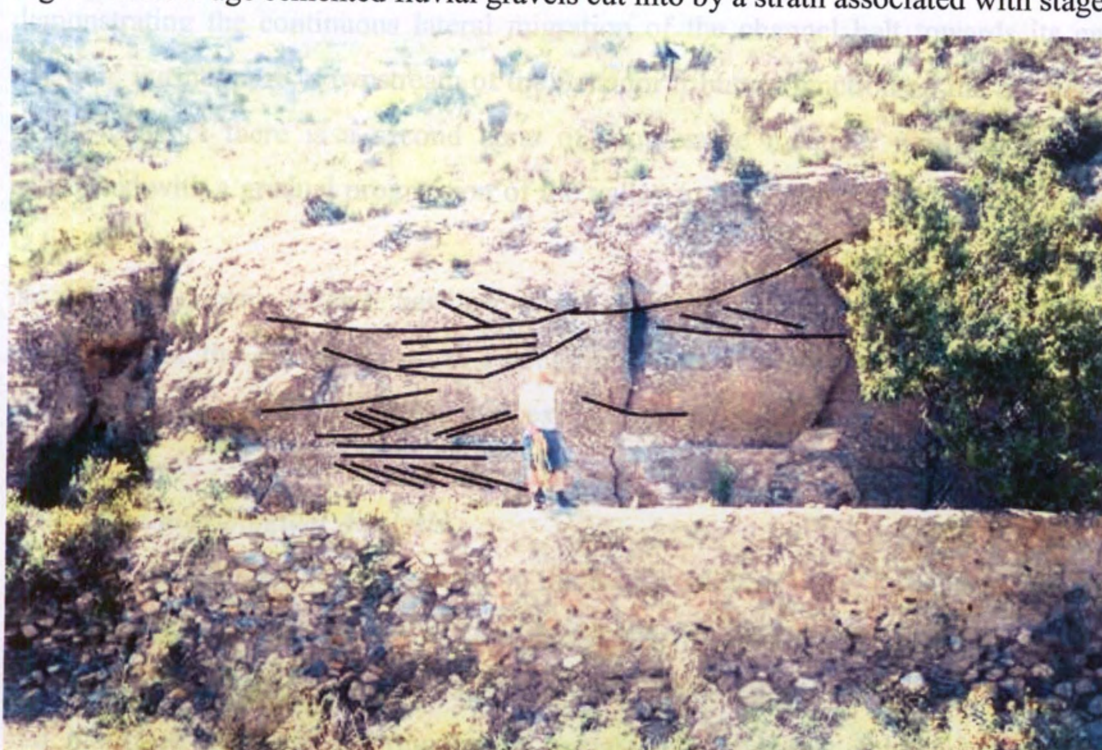


Figure 4.5.7. Terrace B deposits associated within the large abandoned meander shown in Figure 4.5.4. Channel structures and lateral accretion surfaces sketched. Person is 1.85m.

4.5.4 Terrace C

4.5.4.1 The Terrace Record

Remnants of terrace C are well preserved through the El Saltador sub-reach, dominantly in strath form (Figure 4.5.1). Terrace deposits are preserved along the Rambla del Saltador associated with terraces developed at c.10-15m above the modern channel. In the area adjacent to the Barranco del Arto the incisional base of the deposits is preserved at c.10m above the modern channel ((Figure 4.5.8) dissected by the Barranco del Arto and not the main Saltador channel to the south). Strath forms associated with terrace C development along the Saltador tributary are c.10-15m above the modern channel.

Along the main channel of the Rio Alias, strath development is c.15m above the modern channel. Terrace C is preserved on the southern side of the river at the Satlador/Alias tributary junction at c.20m above the modern channel. The incisional base of the deposits is not observed at this location.

Terrace C is often associated with the progressive development of meander loops throughout the coastal reach. In the area immediately downstream of the village of Llano don Antonio (Figure 4.5.1) terraces C, D and E form a progressive suite of terrace levels demonstrating the continuous lateral migration of the channel belt towards its current position. Furthermore, downstream of the Saltador tributary junction on the northern side of the channel there is a second zone of progressive meander migration, this time associated with a gradual progression of the valley to the south from terrace B to terrace D times.

No soil or pedogenic calcrete has been found capping the gravels associated with terrace C throughout the El Saltador sub-reach, however, where terrace gravels have been preserved they are often associated with extensive groundwater cement (Figure 4.5.8).

4.5.4.2 Sedimentological Analysis

Terrace C deposits are best preserved on the Rambla del Saltador, in the area adjacent to the Barranco del Arto, and on the Rio Alias at the Alias/Saltador tributary junction. The terrace C sediments preserved adjacent to the Barranco del Arto are heavily cemented and indurated due to the formation of a massif groundwater calcrete. Consequently analysis of the sedimentary structures is not possible. The deposits preserved on the southern side of the channel at the modern day Saltador/Alias tributary junction, are spatially limited but some idea of fluvial behaviour at this location can be gained.

Figure 4.5.9 is a sketch log of the fluvial gravels associated with terrace C. The sequence is dominated by a fine sand/silt unit with subordinate gravel horizons and possible palaeosol horizons within the deposit. The gravel layers are up to 10cm thick and show lamination within the unit. The finer sandy/silty layers show little structural organisation with faint traces of lamination. However, there is a large erosional horizon dissecting the section diagonally from the top right hand corner to the bottom left hand corner. Above (and to the left) of this horizon is a stratigraphically younger deposit initially of fluvial gravels, then of sandy/silty units and finally a return to fully tractional gravel deposits at the top of the section. The section is 6m in height so the erosional scour has a relief of at least 6m.

The sequence is interpreted as containing dominantly over-bank and colluvial deposits sourced from the easily erodible volcanic hillslopes surrounding this part of the system. Furthermore the active channel belt must have been migrating away from this position allowing the build-up of fine sediments and explaining the lack of coarse bedload (an idea that is supported by the terrace assemblage). The large erosional horizon indicates re-establishment of the channel belt in this location and, importantly, suggests a significant change in local system dynamics leading to incision during what is a regional climatic aggradational phase (Macklin et al., 2002).

4.5.5 Terrace D and E

4.5.5.1 The Terrace Record

Terrace D is preserved along the main trunk of the Rio Alias at 5-10m above the modern channel. Erosional straths are common along the coastal stretch of the Rio Alias, often as part of a series of terrace levels developed adjacent to each other in response to the gradual and persistent lateral migration of the channel in a single direction. The terrace assemblage on the Rio Alias (downstream of the Saltador/Alias junction) suggests a valley planform similar to that of the modern channel.

Terrace D on the Rio Alias upstream of the Saltador junction is preserved dominantly as an erosional strath between 5-10m above the modern channel. However, where terrace D sediments are preserved at the head of the sub-reach, the incisional base of the deposits is below that of the modern channel. Within the series of terraces B, C, D and E in the area adjacent to the village of Llano don Antonio, it is not clear to what extent anthropogenic manipulation of the lower terrace surfaces has affected both the preservation of original

Figure 4.5.8a. Terrace assemblage at the tributary junction of the Barranco del Arto and the Rambla del Saltador. Terrace levels indicated.

Figure 4.5.8b. Terrace C sediments on the Rambla del Saltador/Barranco del Arto tributary. Groundwater calcrete has cemented the deposits.

Figure 4.5.9. Terrace C sediments at the tributary junction of the Rambla del Saltador and the Rio Alias. The unit is dominated by silty-sandy deposits with fluvial gravels at the base and a large erosional horizon indicated at the top of the photograph.

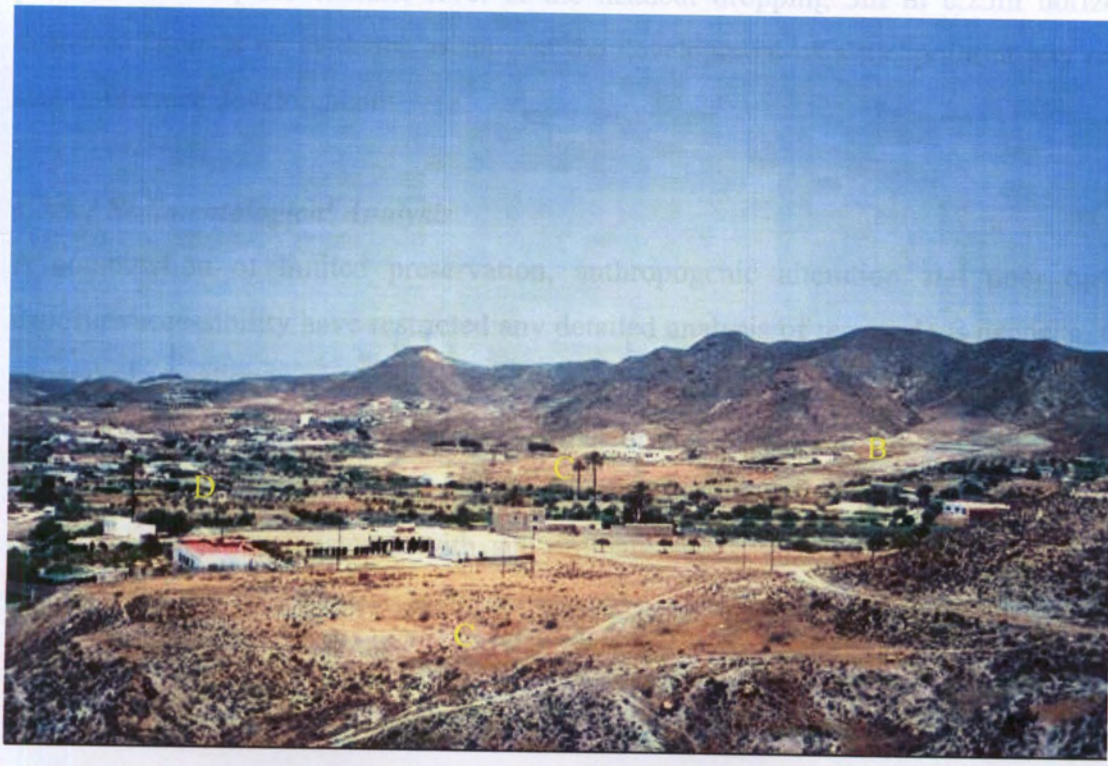


Figure 4.5.10. Terrace assemblage at the head of the Llano don Antonio sub-reach. Levels indicated.

depositional surfaces and/or sediments (Figure 4.5.10). It is likely that some alterations to the land surface have been made both for agricultural and for dwelling purposes.

Along the tributary Rambla del Saltador, there is preservation of terrace D both as depositional surfaces with associated gravels and as erosional straths. The surface is generally less than 10m above the modern channel, and where sediments are preserved the base is below the level of the modern channel. No soils have been preserved capping the terraces of the Rambla del Saltador, and no cementation is evident within terrace deposits, of either groundwater or pedogenic origin.

Terrace E is preserved throughout the El Saltador sub-reach (Figure 4.5.1). It is however, dominantly an erosional strath or at a level consistent with that of the modern floodplain. Consequently detailed analysis of terrace E (Figure 4.5.11) throughout the distal portion of the Rio Alias is not possible.

The head of the basin is defined by the development of a nickpoint developed in the Cuevas Viejas sandstone unit (Figure 4.5.12a) characterised by a calcareous shelly facies unit at this location (Figure 4.5.12b). The modern nickpoint is c.7km upstream of the present coastline, the channel level at the headcut dropping 3m in c.25m horizontal distance. There is no evidence to suggest the development of a nickpoint at any earlier stage of terrace development.

4.5.5.2 Sedimentological Analysis

A combination of limited preservation, anthropogenic alteration and poor outcrop exposure/accessibility have restricted any detailed analysis of terrace D/E deposits. Only general observations regarding particle size and the tractional nature could be made; no analysis of sedimentary structures could be performed. Particle size analysis of the coarse (bedload) component will be discussed fully in Chapter 5. The deposits characteristically comprise gravel size material with sub-ordinate sands and cobble/boulder beds. The nature of the deposits suggests a similar clast assemblage and mode of deposition to the modern channel.

4.5.6 Palaeo-environmental Synthesis

4.5.6.1 Terrace A

Terrace A is poorly preserved and only limited inferences can be made regarding the environment of deposition and controlling factors upon the fluvial behaviour at that time. Terrace A preservation is limited to the head of the sub-reach, the sediments have an unconformable contact with the underlying calc-alkaline volcanics. The sediments preserved suggest that on exiting the canyon developed within the resistant Cuevas Viejas sandstone, the river system was able to easily erode the weaker volcanic rocks and expand to form a wide valley. This is reflected in the deposits associated with terrace A; sediments deposited in sheetflood style displaying some lateral accretion and limited channelisation. Up-sequence the sedimentology suggests a fluvial system characterised by braided streams that are cut, and then filled over several events. The lack of any further deposits of terrace A down-system prevents any interpretation to be made regarding fluvial evolution in terms of climatic and or eustatic controls.

4.5.6.2 Terrace B

Terrace B is well preserved throughout the coastal stretch of the Rio Alias. However, the strath forms preserved along the Rambla del Saltador cannot contribute to our interpretation of the mechanisms controlling fluvial system evolution during the development of terrace stage B.

During aggradation of terrace B the preserved sedimentary sequence suggests that the river evolved as a braided system, the channels exhibiting average depths of c.1m and the sediment load being dominated by gravel and pebble sized material. The planform development of the river valley and the level of the incisional base of the associated terrace deposits reveal a much more complicated picture of drainage evolution here during the development of terrace B than elsewhere.

The incisional level of terrace B has a steep gradient, at c.25m above the modern channel (B1 on Figure 4.5.1) to below the modern channel (B2 on Figure 4.5.1). This incisional relief is taken up largely within the abandoned meander loop (Figure 4.5.4) that is c.2-3km in length developed on the southern side of the channel.

4.5.6.3 Terrace C

Palaeoenvironmental synthesis of terrace stage C is difficult due to the limited preservation of associated gravel deposits. However, the planform development of terrace

Figure 4.5.11. Terrace E preserved in the lower reaches of the Rio Alias. Level indicated by disused buildings.

Figure 4.5.12a. Nickpoint development delimiting the head of the sub-reach.

Figure 4.5.13. Marine sediments preserved south of the mouth of the Rio Alias. Cemented quartz pebble conglomerates are preserved c.30m above modern sea-level. Exit point of the Rio Alias is noted by the arrow.

Figure 4.5.12b. Shelly beds within the Cuevas Viejas sandstone associated with the nickpoint developed at the head of the sub-reach.

C (Figure 4.5.1) suggests a meandering river valley with a greater sinuosity than the modern system. The base of terrace C gravels is not seen in association with a terrace surface, however recent anthropogenic bulldozing of terraces on the lower part of the system has revealed cemented fluvial gravels, that are indurated and likely to be stage C or older. The location is consistent with the valley position during the aggradation of terraces B and C. However the unit has no apparent continuity with the preserved B deposit and is more likely to be associated with terrace C. The base of the deposit is again below the modern river channel.

The (climatically induced ?) incision prior to terrace stage C, evident across the drainage basin of the Rio Alias as a whole, was not, generally able to incise to a level below that of the modern channel, the incisional level generally c.10m above the modern channel. The fact that at the seaward end of the system the base of C falls below the modern channel and below modern sea-level, suggests that the incisional episode prior to the aggradation of terrace C was related here not just to climatic forcing but to local base-level lowering associated with a sea-level fall. Similar to the mode of development proposed for terrace B, it is inferred that the base-level lowering caused by falling sea-level stimulated a wave of incision during a period of otherwise regional aggradation.

Within the terrace C deposits there is a marked erosional surface with at least 6m of relief (Figure 4.5.9). The deposits are fine grained and are interpreted as locally derived slope material sourced from the volcanic hillslopes behind and were located in an area away from the active channel belt. Gravels and sands dominate the sedimentary sequence. The erosional horizon is significant as it suggests re-establishment of the active channel belt in this location and also represents a substantial incisional event within the aggradational sequence. The distinct lack of coarse bedload material above the erosional horizon suggests that this is not due to a large flood. The erosional horizon may be indicative of a change in fluvial regime, a within-sequence switch to incision produced by a fluctuating base-level ? It is difficult to make a more detailed reconstruction of the fluvial evolution during the stage C as there is only one clear exposure of the terrace C sedimentary sequence.

4.5.6.4 Terrace D and E

As with the older terrace units sediment preservation is limited on terrace D and E. As in the drainage basin as a whole, the level of the incisional base of the deposits is below the level of the modern channel. The preserved strath/terrace surfaces along the Rio Alias suggest that the river valley was meandering towards its present position during the development of terraces D and E. The river was grading to a level below that of the modern day channel, and if consistent with the mode of evolution of the earlier terrace stages, to a sea-level lower than that of the present day Mediterranean Sea.

4.5.7 Quaternary Coastal Sediments

4.5.7.1 Introduction

Quaternary marine sediments have been described from around the southeastern Mediterranean coastline of Spain, and attempts have been made to relate these sequences to Oxygen Isotope Stages throughout the Quaternary and to the evolving terrestrial fluvial systems (see Chapter 6 in Mather et al., 2002 for more detail). No coastal deposits have been previously described from the coastline north of Carboneras associated with the Rio Alias (Figure 4.5.1).

4.5.7.2 Coastal sediments

Two levels of raised beach deposits are located just south of the mouth of the Rio Alias, north of the town of Carboneras (Figure 4.5.1). The lowest unit is preserved up to c.8m above modern sea-level and the higher unit at c.30m above sea-level (Figure 4.5.13). Both units consist of an in-situ degraded, cemented quartz conglomerate. The quartz pebbles are extremely well rounded and in places some evidence of aeolian-dune preservation is exhibited as a cemented fine-sandstone unit.

4.5.7.3 Links with the terrace sequence?

No absolute dating has been performed on the sediments and there is no inter-digitation of fluvial and coastal sediments to suggest a chronological relationship. However some general interpretations regarding the marine deposits and Quaternary global sea-level fluctuations can be made and tentative links with the terrace sequence presented.

Both raised beach deposits (at c.8m and c.30m above modern sea-level) are likely to relate to previous sea-level highstands associated with northern hemisphere interglacials. The intervening glacial periods would lead to a fall in sea-level and the developing river systems would consequently incise to a level below that of the modern sea-level. This incision wave would be expected to propagate upstream and would be reflected in the incisional base of the terrace deposits.

The evidence preserved through the lower reaches of the Rio Alias suggests both terraces B and C, and probably terrace D, developed steep incisional profiles through the coastal portion of the system. Given the inferred relative timing of the incisional/aggradational events in the glacial/inter-glacial cycle the climatically driven incisional event would have occurred at the same time as a sea-level highstand. The impact of the glacial inter-glacial cycle on sea-level and the evolution of the distal portion of the Rio Alias will be discussed further in Chapter 7.

Accepting that climate controls the overall incisional/aggradational regime of the river system, and that incision will coincide with inter-glacial phases, the incisional event preceding the aggradation of terrace B would have occurred during a high sea-level stand and consequently the degree to which the system would incise would be limited by the relative sea-level position acting as local base-level. It is suggested that the wave of incision associated with the steepened gradient during the incision preceding terrace B through this stretch of the Rio Alias, was driven by the onset of glaciation and the consequent sea-level fall.

The fall in sea-level would greatly decrease the local base-level, and an incisional wave would be generated. It is proposed that the fall in sea-level would drive an incisional wave headwards initially overcoming the regional climatically generated aggradational pulse. When the fluvial system had adjusted to this fall in base-level by fluvial incision and an increase in valley length via the development of large meander loops, the pulse of sediment generated by de-stabilisation of the hillslopes was re-established and aggradation could ensue. The terrace deposits buried this incisional relief and presumably prograded to zones now offshore.

It is postulated this mode of development was consistent during the evolution of terraces B and C and possibly also terrace D. Furthermore, base-level lowering and adjustment of the fluvial system could also explain the lack of preservation of sedimentary sequences within the coastal reach of the Rio Alias. The generation of an incision wave could lead to a local stripping of the unconsolidated conglomerates previously deposited.

The effects of the interaction of climatic variations and eustatic sea-level and consequent base-level fluctuation on the Quaternary evolution of the Rio Alias are discussed in detail in Chapter 7 together with questions relating to dating the sequence as a whole.

Chapter 5
Sediment Provenance Ascription

Abandoned meander and deformed Quaternary fluvial sediments, Argamason

Chapter 5
Sediment Provenance Ascription

Chapter 5

Sediment Provenance Ascription

5.1 Introduction

In order to fully understand the evolution of fluvial systems it is important to understand the sediment-source linkages. In gravel-bed rivers such as the Rio Alias, this can be attempted by examining the provenance characteristics of both the coarse sediment assemblage (B axis >2cm: bedload) and the fine sediment assemblage (<2mm: suspended load). The transportational processes may well be different for the bedload and suspended load (Woodward et al., 1992) and consequently the lithological characteristics may be very different at any one location. However it is important to assess the degree of association between the lithological/mineralogical properties of the bedload and suspended load in any attempt to model the long-term evolution of the fluvial system. Previous studies within southeast Spain (e.g. Mather, 1991; Mather, 1993b; Mather and Harvey, 1995; Harvey and Wells, 1987; Harvey et al., 1995; Stokes, 1997; Stokes and Mather, 2003) have utilised the provenance characteristics of the bedload material within alluvial deposits to determine patterns of drainage evolution, and more importantly drainage re-organisation by river capture. There have however, been no attempts to examine the long-term drainage evolution of these systems by examining both the coarse and fine sediment assemblages, shown to be successful elsewhere (i.e. the Pindus Mountains, Greece: Woodward, 1990; Woodward et al., 1992).

The drainage basin of the Rio Alias is characterised by metamorphic, sedimentary and volcanic bedrock zones, and the Alias therefore is suitable for studies regarding provenance variation (Figure 5.1).

5.2 The Modern System

5.2.1 Introduction

In order to make any attempt to reconstruct the long-term provenance characteristics of the Rio Alias, the modern day system first needs to be examined. If a thorough understanding of how the modern transportational processes operate can be gained, then the application of this technique to the terrace record would be viable and appropriate for addressing questions of long-term drainage evolution. In this chapter both the coarse and fine load material will be examined using the techniques discussed in Chapter 3.

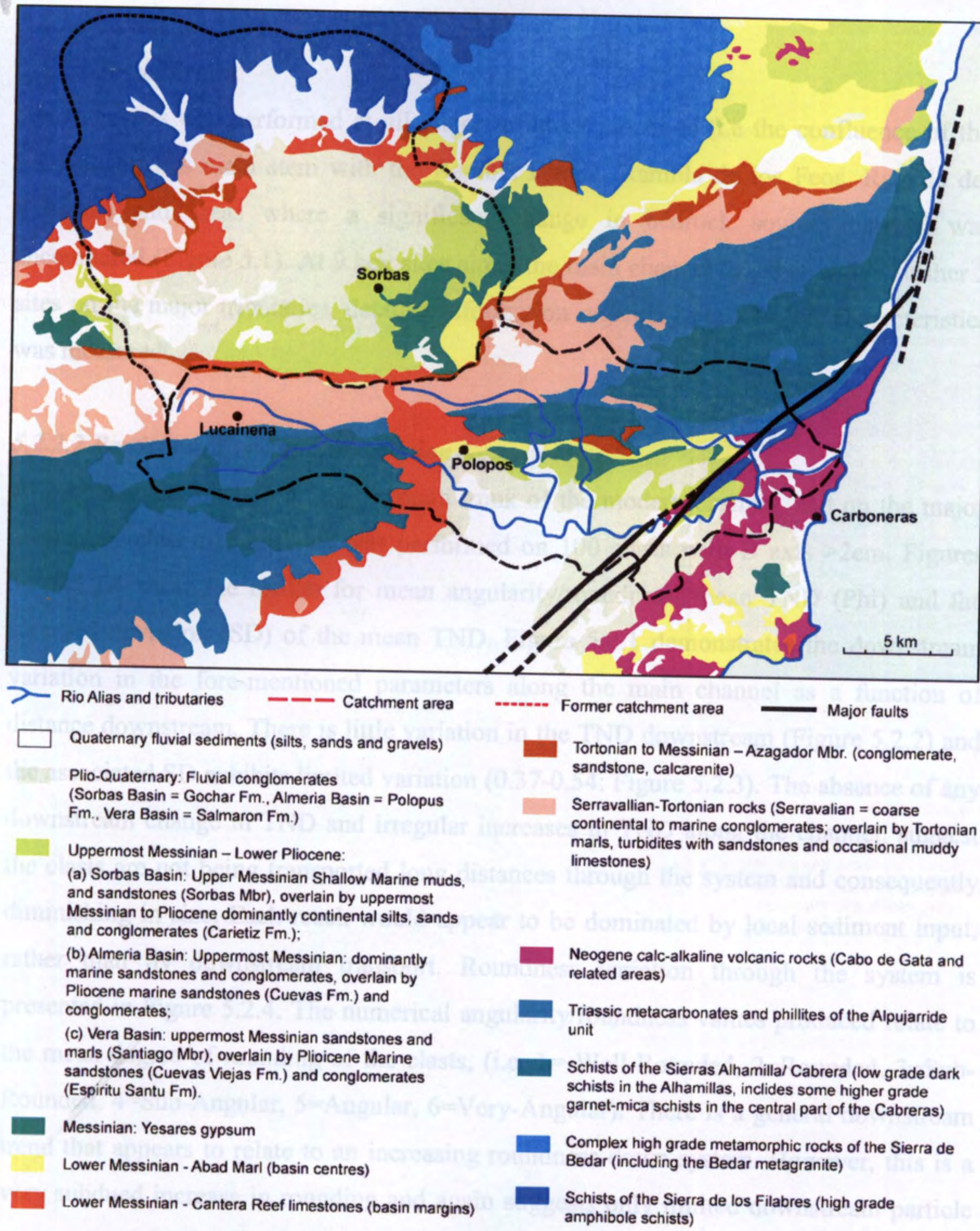


Figure 5.1. Geological map of the study area.

5.2.2 Bedload

5.2.2.1 Introduction

Clast analysis was performed at all major tributary junctions (i.e the confluence of the Lucainena/Alias main stem with the Rambla Honda, Rambla de los Feos, Rambla del Saltador) and areas where a significant change in bedrock source material was encountered (Figure 5.1). At 9 key sites along the main channel together with a further 3 sites on the major tributaries, detailed information regarding particle size characteristics was measured.

5.2.2.2 Particle size and shape variation

At each sample location along the main trunk of the modern channel, and on the major tributaries, clast size analysis was performed on 100 clasts with B axis >2cm. Figures 5.2.1-5.2.4 show the results for mean angularity/roundness, mean TND (Phi) and the standard deviation (SD) of the mean TND. Figure 5.2.1 demonstrates the downstream variation in the fore-mentioned parameters along the main channel as a function of distance downstream. There is little variation in the TND downstream (Figure 5.2.2) and the associated SD exhibits limited variation (0.37-0.54: Figure 5.2.3). The absence of any downstream change in TND and irregular increases in TND along the channel, suggest the clasts are not being transported long distances through the system and consequently diminishing in size. Each reach would appear to be dominated by local sediment input, rather than by downstream transport. Roundness variation through the system is presented in Figure 5.2.4. The numerical angularity/roundness values produced relate to the mean degree of rounding of the clasts, (i.e. 1= Well-Rounded, 2=Rounded, 3=Sub-Rounded, 4=Sub-Angular, 5=Angular, 6=Very-Angular). There is a general downstream trend that appears to relate to an increasing roundness down-system. However, this is a very subdued increase in rounding and again suggests only limited downstream particle transport and related diminution.

Zone 1 (on Figure 5.2.2) is the tributary junction between the Lucainena/Alias and the Rambla Honda (in the Lucainena sub-reach) and here the clasts are characteristically sub-rounded. Further downstream towards zone 2 (Figure 5.2.2), the confluence of the Rio Alias and the Rambla de los Feos, the clasts are characterised by rounded clasts. Continuing downstream to zone 3 (Figure 5.2.2), the Alias/Rambla del Saltador

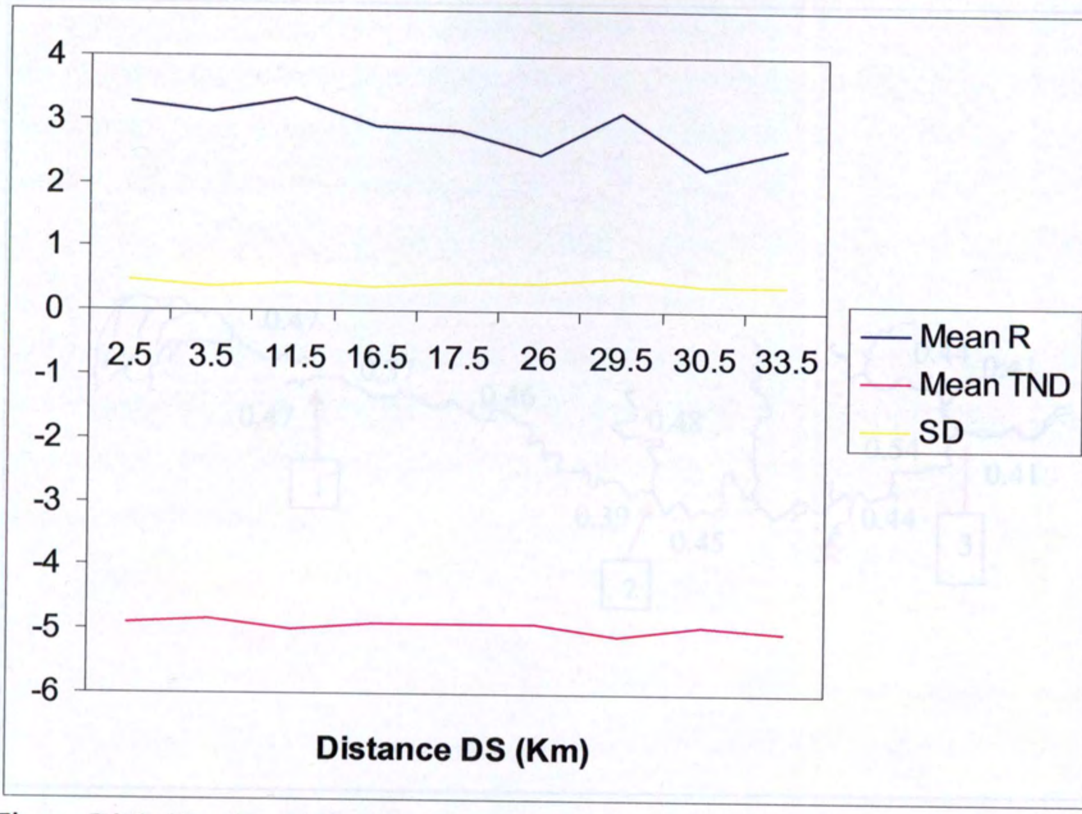


Figure 5.2.1. Graph to show downstream variation in Mean Roundness (Mean R), Mean TND (Phi) and Standard Deviation. Distances downstream represent significant tributary junctions, bedrock variation and the coast (see text).

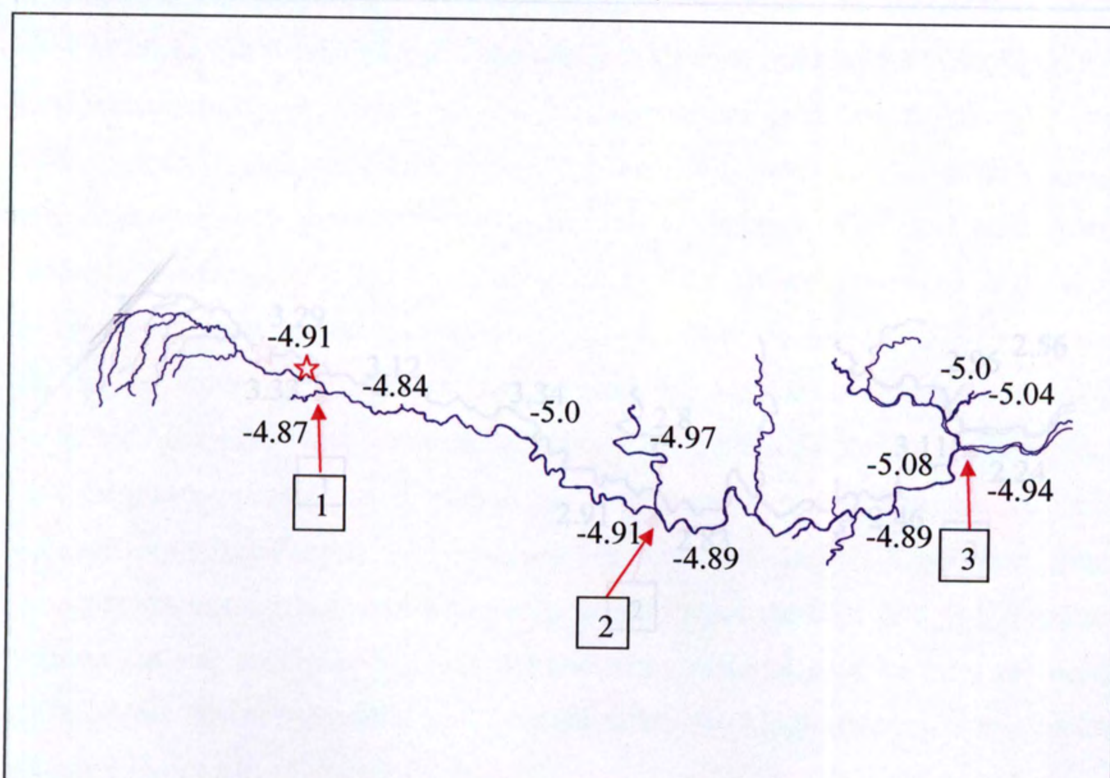


Figure 5.2.2. Mean TND (Phi) for the Rio Alias and its major tributaries. For locations see text. For location of star see text. Star indicates Polopos village.

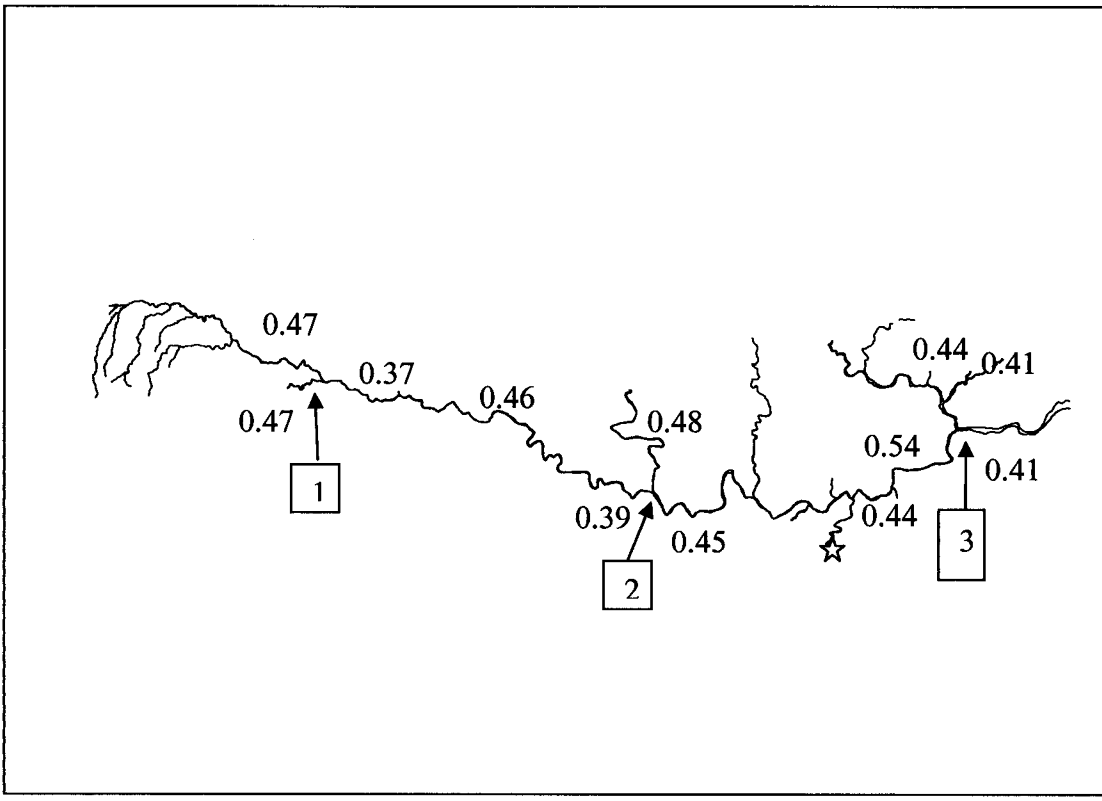


Figure 5.2.3. Standard Deviation of the Mean TND for the Rio Alias and its major tributaries. For locations see text. Star indicates Palmerosa tributary.

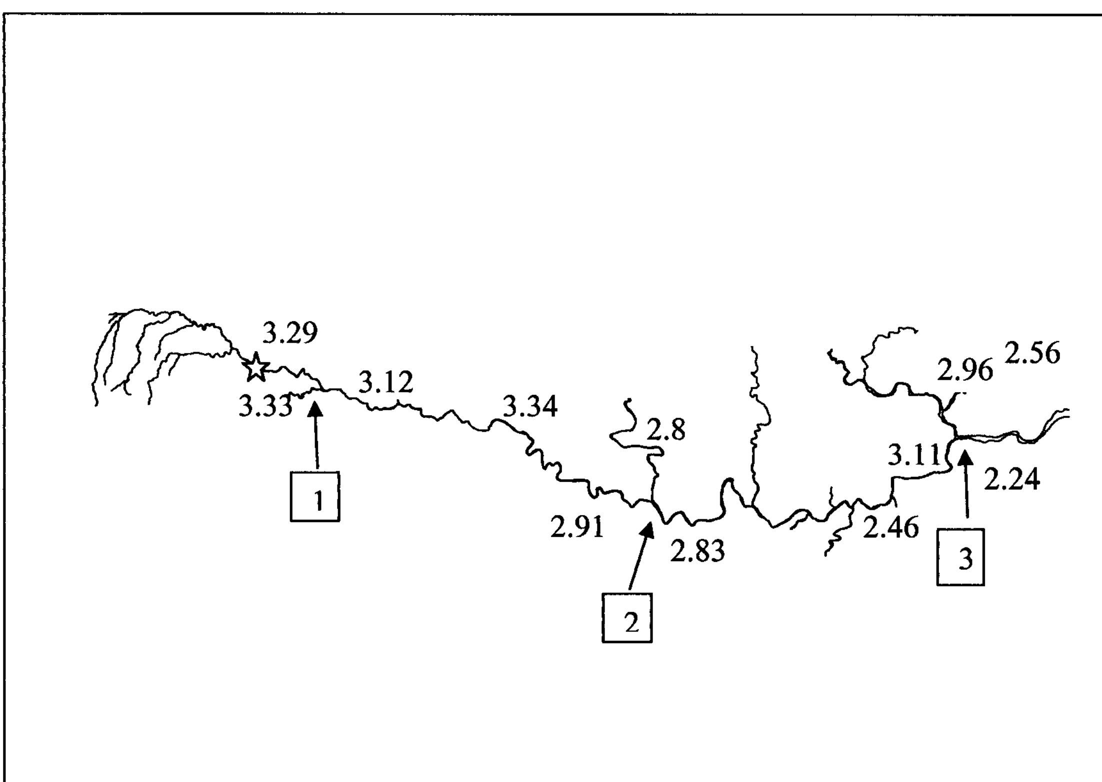


Figure 5.2.4. Mean roundness values (for explanation see text) for the Rio Alias and its major tributaries. For locations see text. Red star indicates Barranco El Campillo.

confluence, the clasts generally appear rounded with the exception of those on the Rio Alias prior to the Saltador confluence. This may be attributed to the outcrop of volcanic rocks in this area, primarily weathering to a more angular material, before winnowing quickly in to the fine component.

Particle size and shape data exhibit very little variation throughout the Alias drainage basin. Basin-wide, angularity/roundness shows limited increasing roundness downstream and there is no apparent downstream fining in particle size. Results suggest that the coarse material input into the system is dominated by local sediment input, and consequently particles are not increasing significantly in roundness or decreasing in size through the system.

5.2.2.3 Lithological variation of the clast assemblage

The lithological units for clast analysis have been simplified for the presentation of the results. Alpujarride material includes: schist, meta-carbonate, quartz and fault rock. Sandstone includes: all Neogene sandstone, and Carbonate/Gypsum includes the very limited number of gypsum clasts recorded and all the Neogene limestone clasts.

a) The Lucainena Sub-Reach

The Lucainena sub-reach defined in the previous Chapter drains a mixture of lithological units including: Alpujarride schists and meta-carbonates, Iron Ore, fault rock, Neogene marls, limestones and sandstones. Figures 5.2.5 is a sequence of pie charts exhibiting the downstream/tributary junction variation in clast assemblage. The clast content of the headwater systems of the Rio Alias, the portion of the system referred to as the Rambla de Lucainena (for exact location refer to Figure 4.2.2) is identified on Figure 5.2.5. Both streams are dominated by material derived from the Alpujarride complex sourced from the Sierra Alhamilla immediately to the south. The Rambla del Penoncillo however, has an increased proportion of limestone and sandstone material. The majority of the drainage area of the Rambla del Penoncillo lies in Neogene basin-fill, here dominated by calcareous sandstones and reef limestones. Downstream the Barranco el Campillo (for position see star on Figure 5.2.2) is dominated by material sourced from the northern flank of the Sierra Alhamilla and is dominated by Alpujarride material, including abundant fault rock.

Figure 5.2.5 demonstrates the variation around the Rambla Honda confluence (tributary junction 1 on Figure 5.2.2). The Rambla Honda drains a catchment of almost 100% schist and this is reflected in the clast content. The main trunk stream at this location reflects the input of both Alpujarride material from the mountains and sandstones and limestones from the Neogene basin fill. However, downstream of the confluence the dominant supply of coarse grade material appears to be from the Alpujarride complex sourced from the Rambla Honda tributary. It may be a characteristic of ephemeral streams for the smaller tributary system to supply greater amounts of sediment to the main stream within a flood event, and consequently dominate the sediment assemblage.

b) The Polopos Sub-Reach

The Polopos sub-reach is located dominantly within Neogene basin-fill sediments (i.e. sandstones, limestones, conglomerates) on the southern side of the Sierra Alhamilla/Cabrera (refer to Figure 4.3.1). However the main channel of the Rio Alias and the Rambla de los Feos drain across the mountain belt prior to their confluence downstream of Polopos (tributary junction 2 on Figure 5.2.3), and consequently are sourced largely in metamorphic sediments of the Alpujarride complex.

Polopos village (star on Figure 5.2.2) is at the head of the sub-reach and the lithological assemblage is dominated by the metamorphic complex, with <25% limestone material sourced from the basin-fill sediments (Figure 5.2.5). Upstream of Polopos a canyon is developed through reef material, and it would appear the resistance of this material to erosion is limiting the amount of input to the stream bedload. 2km downstream of Polopos there is a limited change in the bedload composition with an increasing proportion of basin-fill material represented (Figure 5.2.5) as the river drains across local lithologically softer Cuevas Viejas sandstone.

The Rambla de los Feos, and the Rio Alias downstream of the confluence, drain Quaternary fluvial deposits (terraces A-C) containing high-grade metamorphic sediments sourced from the Sierra de los Filabres prior to the Rio Aguas capture event (Maher et al., in press). The hornblende schist is thus introduced to the lithological assemblage of the modern channel, allbeit in small proportions (Figure 5.2.5). Excluding the hornblende schist, the source area of the Rambla de los Feos is very similar to that of the upstream portion of the Rio Alias and this is reflected in the clast content of the channel sediments (Figure 5.2.5). Alpujarride material dominates the assemblage with basin-fill sands and carbonates representing around 30% of the total assemblage. The input from the local outcrop of the Cuevas Viejas sandstone has increased relative to the Polopos area due to the increasing surface area coverage of the sandstone unit.

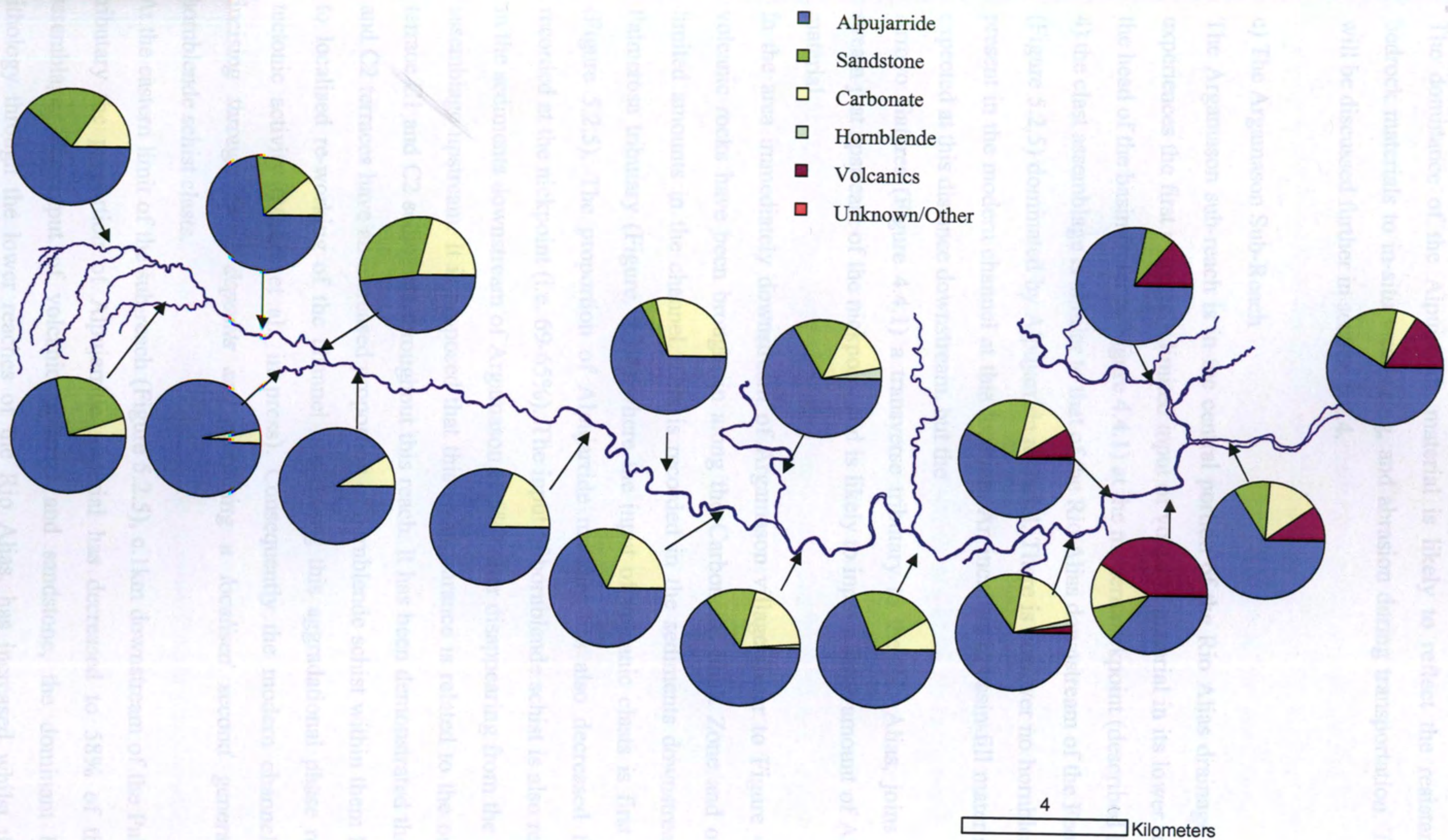


Figure 5.2.5. Clast compositional analysis for the modern channel of the Rio Alias. N=200.

The dominance of the Alpujarride material is likely to reflect the resistance of the bedrock materials to in-situ weathering, and abrasion during transportation. This theme will be discussed further in section 5.2.4.

c) The Argamason Sub-Reach

The Argamason sub-reach is in the central portion of the Rio Alias drainage basin and experiences the first extremely limited input of volcanic material in its lower reaches. At the head of the basin (refer to Figure 4.4.1) at the modern nickpoint (described in Chapter 4) the clast assemblage is similar to that of the Rio Alias downstream of the Feos junction (Figure 5.2.5) dominated by Alpujarride material. There is however no hornblende schist present in the modern channel at this location. An increase in basin-fill material may be expected at this distance downstream, but the

Arroyo Gafares (Figure 4.4.1) a transverse tributary to the Rio Alias, joins the main stream just upstream of the nickpoint and is likely to input a large amount of Alpujarride material.

In the area immediately downstream of Argamason village (refer to Figure 4.4.1) the volcanic rocks have been brought in along the Carboneras Fault Zone and outcrop in limited amounts in the channel. This is recorded in the sediments downstream of the Palmerosa tributary (Figure. 5.2.4) where the input of volcanic clasts is first recorded (Figure 5.2.5). The proportion of Alpujarride material has also decreased from that recorded at the nickpoint (i.e. 69-65%). The input of hornblende schist is also recognised in the sediments downstream of Argamason (1.5%) after disappearing from the sediment assemblage upstream. It is proposed that this re-appearance is related to the outcrop of terrace C1 and C2 sediments throughout this reach. It has been demonstrated that the C1 and C2 terraces have an increased proportion of hornblende schist within them here, due to localised re-working of the channel bed during this aggradational phase related to tectonic activity (Maher et al., in press). Consequently the modern channel is now incising through these deposits and producing a localised second generation of hornblende schist clasts.

At the eastern limit of the sub-reach (Figure 5.2.5), c.1km downstream of the Palmerosa tributary the proportion of Alpujarride material has decreased to 58% of the total assemblage. The input of volcanic material and sandstone, the dominant bedrock lithology through the lower reaches of the Rio Alias, has increased whilst the now distally sourced Neogene limestone material is decreasing in proportional percentage.

D) The El Saltador Sub-Reach

The distal portion of the Rio Alias drains an area dominated by Cuevas Viejas sandstone and volcanic bedrock. The Rambla del Saltador is a major tributary to the Rio Alias in the coastal reaches (zone 3 on fig. 5.2.4) and drains the southern flank of the Sierra Cabrera (see Figure 1.1). There is a distinct lithological change at the confluence of the two streams (Figure 5.2.5). Upstream of the Rambla del Saltador confluence the main stream is characterised by a bed-load dominated by volcanics and basin-fill sediments (at 64% of the total assemblage: Figure 5.2.5). This is a significant change in the coarse bedload signature as for the first time the Alpujarride material (i.e. schist, meta-carbonate, quartz and fault rock) does not dominate the assemblage. The upper part of the El Saltador sub-reach is cut dominantly into volcanic material. The volcanic material is easily erodable and quickly diminishes to the fine fraction. Downstream of the Saltador tributary the Rio Alias is confined by a bedrock reach that is cut dominantly in volcanic material. However the volcanic proportion of the assemblage decreases towards the mouth of the river at the coast (Figure 5.2.5). The diminishing volcanic content is inferred to be a function of the rapid abrasion of the relatively weak clasts, forming particles of <2mm B axis.

The upper part of the El Saltador sub-reach (above the tributary junction) also has a significant proportion of carbonate and sandstone (23%) supplied by the Neogene basin-fill rocks. The Alpujarride component decreases at this point reflecting the significant distance from the last major influx of this material (c.9km) upstream.

The Rambla del Saltador is characterised by almost 80 % Alpujarride material and a small amount of volcanic material and sandstone. The results appear to relate directly to the extent of outcrop of lithological units in the feeder area of the Rambla del Saltador, i.e. the dominance of Alpujarride material due to the location of the feeder systems on the southern flank of the Sierra Cabrera.

Downstream of the confluence the signal is initially dominated by the influx of Alpujarride material (Figure 5.2.5). This is not unexpected given the behaviour of tributary junctions in ephemeral streams where tributary streams can often produce more sediment input than the main channel (as at the Rambla Honda junction discussed in section 5.2.2.3 a). Further downstream at the mouth of the river, the sediment assemblage reflects the increasing input of material from the valley sides adjacent to the river channel, as the volcanic and sandstone component increases from 34% 2km upstream downstream of the Saltador confluence to 41% at the coast (Figure 5.2.5).

The clast content of the modern channel indicates the dominance of local sediment supply, and, sediment supply from tributary systems to the bedload component of the system.

5.2.3 The Suspended Load

5.2.3.1 Introduction

In order to assess the provenance variation of the fine sediment assemblage (i.e. the component <2mm in size) a combination of techniques was employed:

- Petrological thin sections were made on samples taken at a series of points along the main stream in order to establish the lithology of the grains constituting the fine sediment load. Petrological thin section analysis was carried out by standard identification and counting of the lithic assemblage. Following the method indicated by the "Nomograph for Determination of Counting Error" taken from Folk (1973), 300 counts were made on each slide in order to limit the degree of error to c.3%.
- Polished thin sections were prepared from samples taken at the main tributary junctions in order to examine the mineral assemblage using the SEM.
- Magnetic measurements were made on samples collected from a series of points along the modern channel, similar to those for the clast analysis.

5.2.3.2 Petrological and SEM analysis

The mineral assemblage recorded on the SEM was noted in a similar manner to the Petrological analysis, counting the number of grains represented in the sample. 150 counts were made on each sample. Grain identification terminology has been simplified (as in section 5.2.2) in order to allow provenance analysis between the clast assemblage and the <2mm fraction. Quartz and carbonate grains receive their own categories. This is due to the impossibility of separating schist-generated quartz from that produced by sandstone lithologies. Similarly the carbonate grains cannot be separated into meta-carbonate (Alpujarride) and carbonate (basin-fill), so one "carbonate" group was recorded.

a) The Lucainena Sub-Reach

Petrological analysis of the grain assemblage (<2mm) was completed on 5 samples within the Lucainena sub-reach (Figure 5.2.6/Figure 5.2.7) two sites indicated by stars on Figure 5.2.6 and 3 sites around the Honda confluence. The results are presented in Figures 5.2.7.and 8. Lithic grains were identified and counted at each site. Figure 5.2.8 exhibits general grain characteristics when viewed in Cross Polarised Light (XPL)

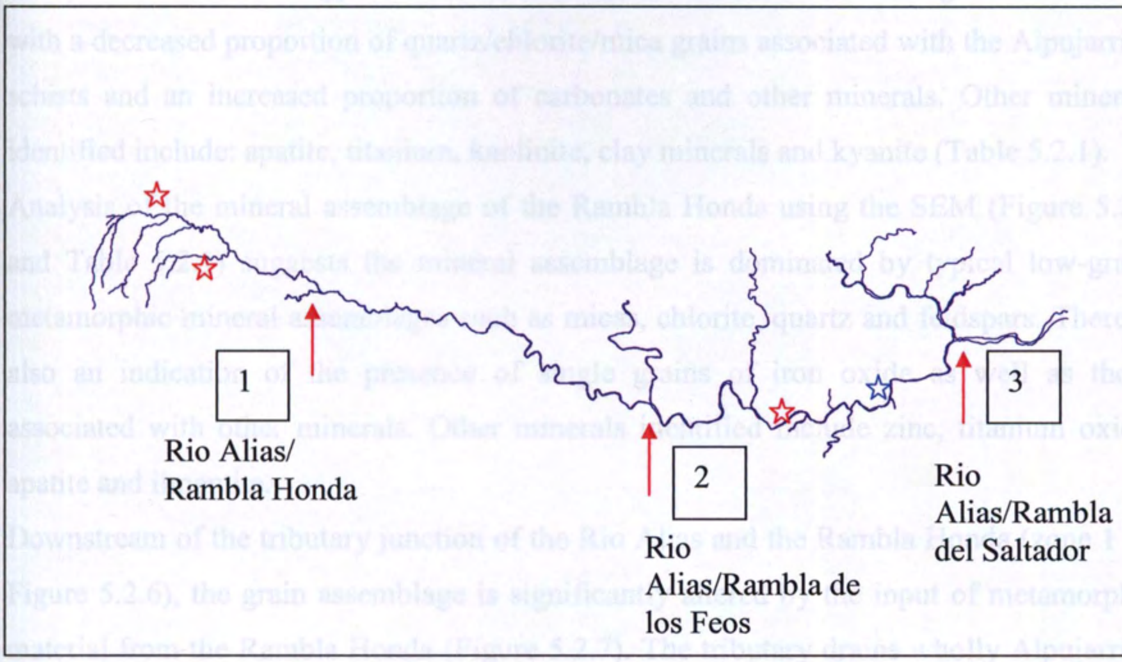


Figure 5.2.6. Sample location points for standard thin section analysis: indicated by red stars and the three major tributary junctions indicated (boxes). SEM analysis was also undertaken on samples from each major tributary junction and the position indicated by the blue star downstream of the Palmerosa tributary.

and characteristic carbonate and schist grains are clearly identified. At the head of the sub-reach, on the Rambla del Penoncillo the lithic assemblage is quite well mixed, with quartz, sandstone/carbonate and Alpujarride material each representing c.1/3 of the total grain content (Figure 5.2.7). The grain assemblage at Lucainena village is different from that of the Rambla del Penoncillo (though both share the same lithological source area material) in that there is a higher proportion of carbonate material. The tributary developed at Lucainena village is sub-parallel to the mountain front boundary between the Alpujarride complex and basin fill material, and consequently incises directly into both materials. The Alpujarride complex is composed of meta-carbonate in this location and the basin-fill material is carbonaceous sandstone. The high carbonate content is likely to reflect local input from both sources.

On the main stream before the Rambla Honda confluence, there is a mixed assemblage dominated by carbonate material and sandstone lithics (Figure 5.2.7). The increasing proportion of sand grains is derived from the Tortonian sandstone incised directly by the modern channel throughout the headwater reaches. The Alpujarride component appears to be decreasing from the upstream areas at Lucainena and the Rambla del Penoncillo.

Analysis of the mineralogy on the SEM also identified a mixed mineralogical assemblage with a decreased proportion of quartz/chlorite/mica grains associated with the Alpujarride schists and an increased proportion of carbonates and other minerals. Other minerals identified include: apatite, titanium, kaolinite, clay minerals and kyanite (Table 5.2.1).

Analysis of the mineral assemblage of the Rambla Honda using the SEM (Figure 5.2.9 and Table 5.2.1) suggests the mineral assemblage is dominated by typical low-grade metamorphic mineral assemblages such as micas, chlorite, quartz and feldspars. There is also an indication of the presence of single grains of iron oxide as well as those associated with other minerals. Other minerals identified include zinc, titanium oxide, apatite and ilmentite.

Downstream of the tributary junction of the Rio Alias and the Rambla Honda (zone 1 on Figure 5.2.6), the grain assemblage is significantly altered by the input of metamorphic material from the Rambla Honda (Figure 5.2.7). The tributary drains wholly Alpujarride metamorphic rocks and the sample is dominated by schist material. This is expressed by the high percentage (49%) of Alpujarride material (excluding quartz or carbonate liberated from the Alpujarride complex). The carbonate and quartz generated along the Rambla Honda can only have been liberated from the Alpujarride complex as the tributary drains only the central portions of the mountain system.

The grain assemblage (Figure 5.2.7) is dominated by Alpujarride material (41%) and a high proportion of quartz (30%), suggestive of dominant fine sediment delivery from the Rambla Honda into the Rio Alias main stream, swamping the signal from the Lucainena headwaters. The mineral assemblage downstream of the Honda junction indicated by the SEM analysis (Table 5.2.1) indicates an assemblage similar to that of the Rambla Honda dominated by mineral assemblages characteristic of schist grains (i.e. quartz, chlorite and mica: see Figure 5.2.10 A-C composition indicators). However, similar to the Lucainena headwaters there is a significant proportion of other minerals including: kaolinite, titanium, ilmenite, apatite, illite and rare earth minerals.

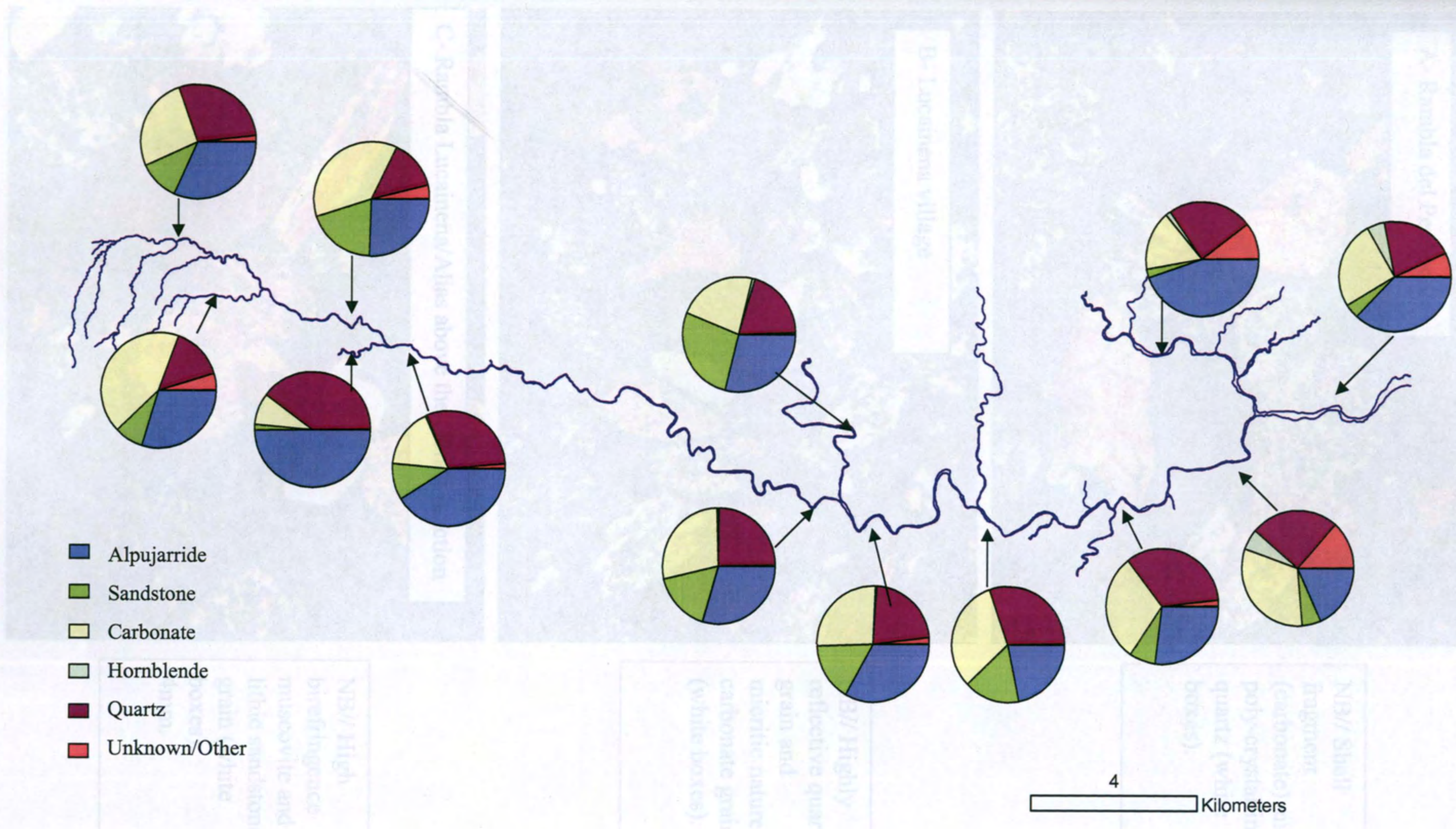
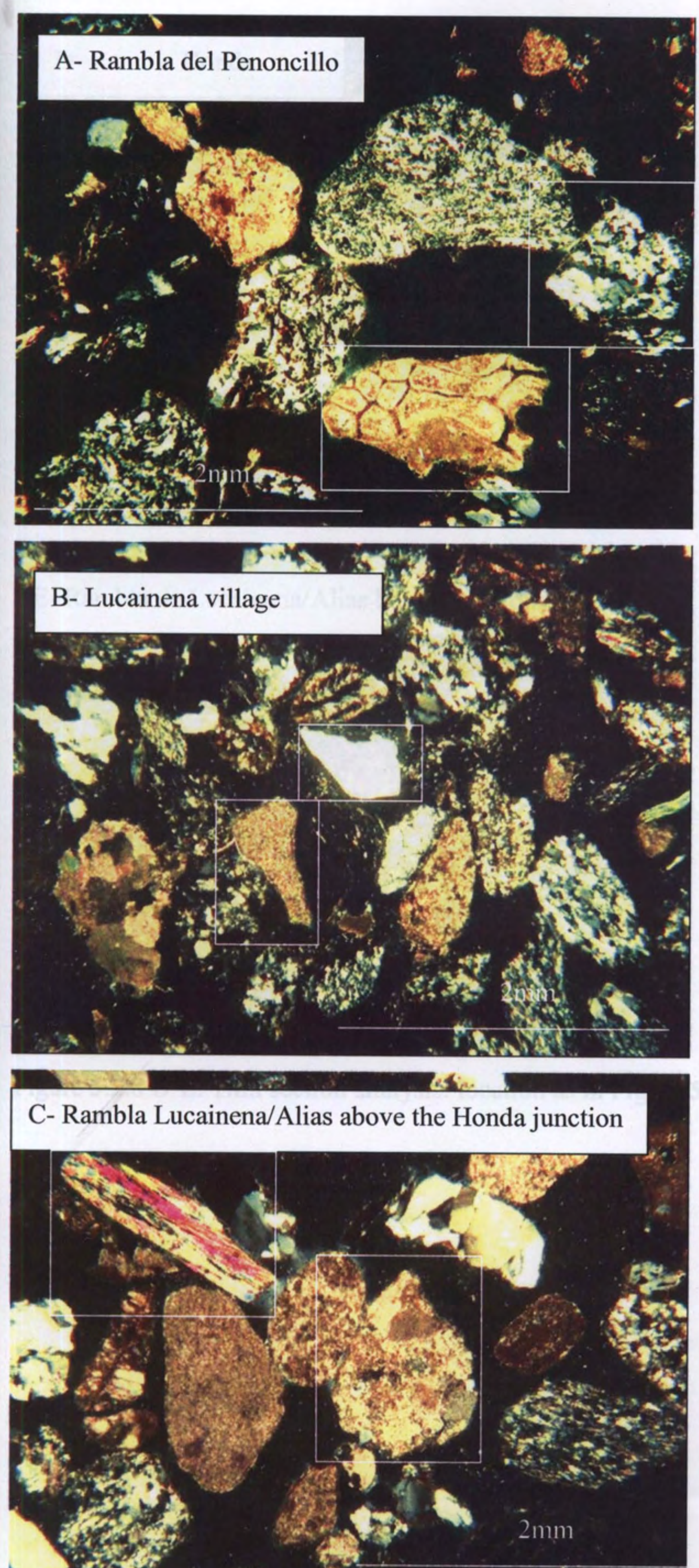


Figure 5.2.7. Lithic grain proportions from petrological thin section analysis on samples taken along the modern channel. N=300.

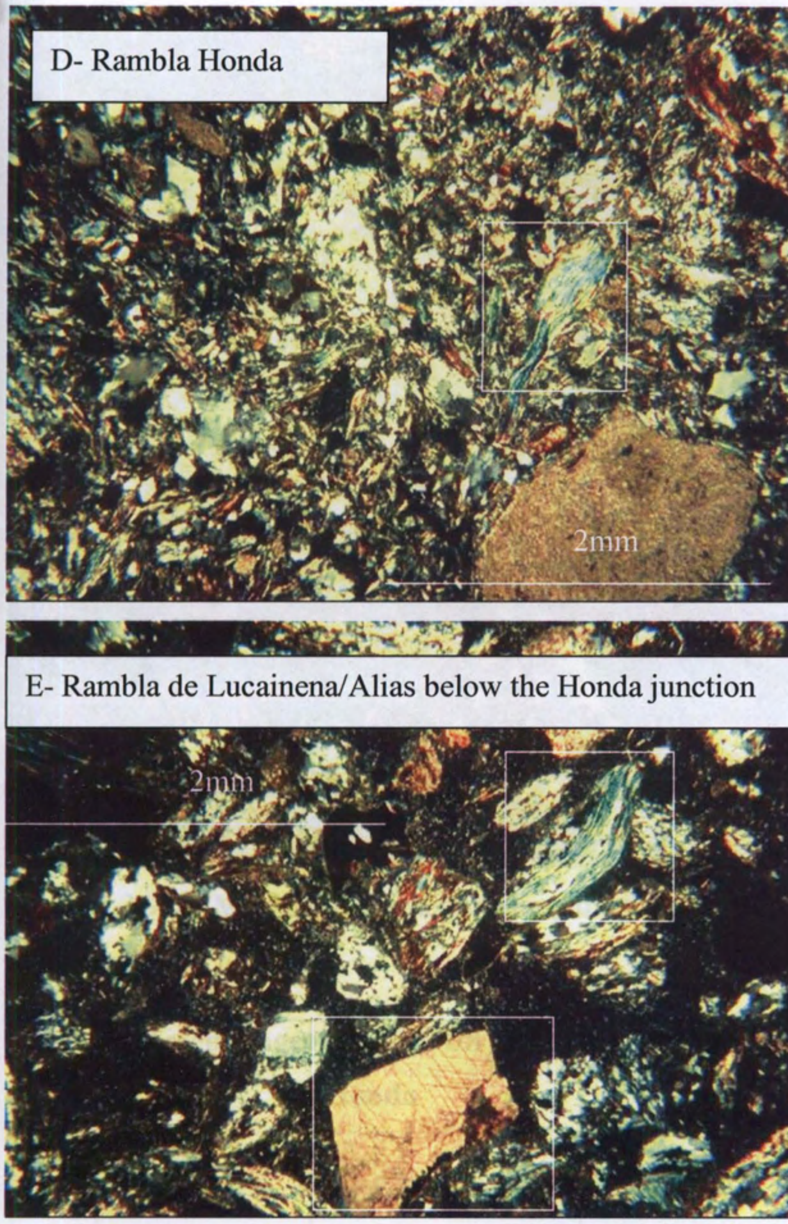


NB// Shell fragment (carbonate) and poly-crystalline quartz (white boxes).

NB// Highly reflective quartz grain and micritic nature of carbonate grains (white boxes).

NB// High birefringence muscovite and lithic sandstone grain (white boxes).
4mm.

Figure 5.2.8 A-C. Thin section analysis: locations as in Figure 5.2.6/7.



NB// Dominance of poly-crystalline quartz and micaceous grain (white box).

NB// Micaceous grain with crenulation cleavage and calcite crystal with intersecting cleavage traces at 75° (white boxes).

Figure 5.2.8 D-E. Thin section analysis: location as in Figure 5.2.6/7.

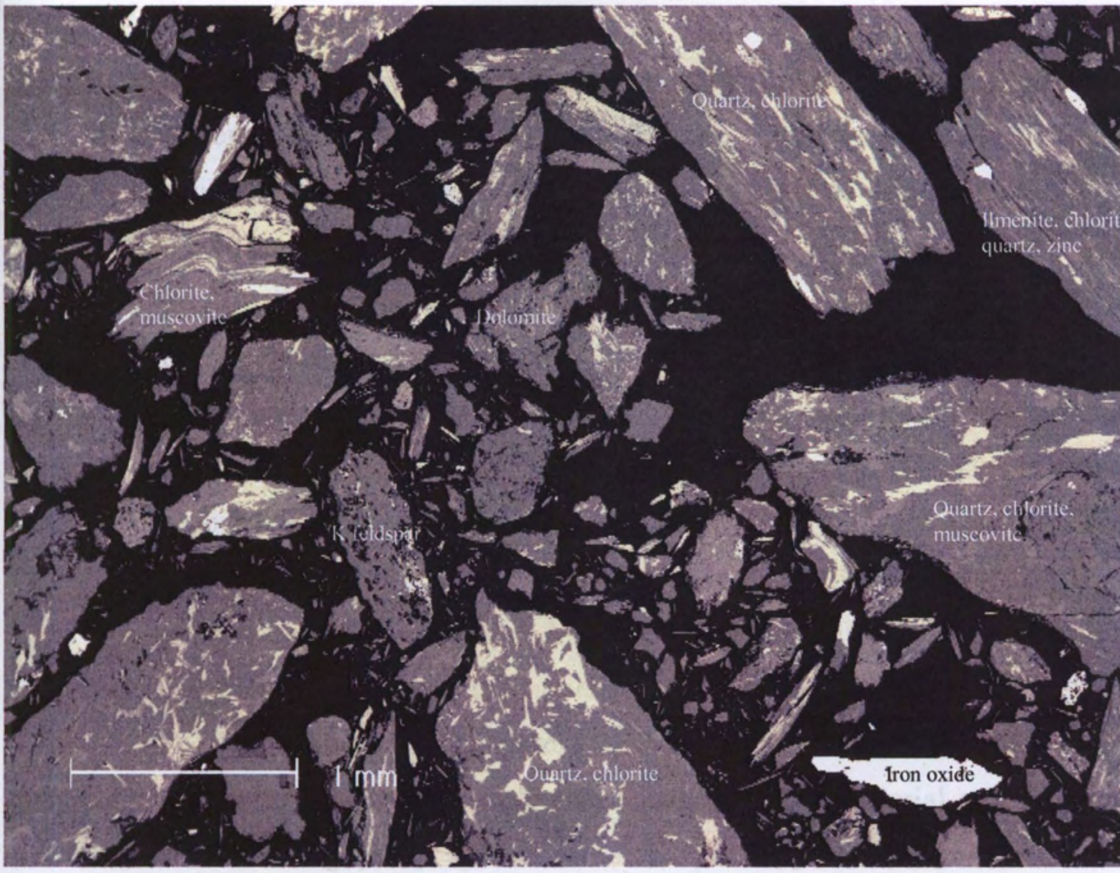


Figure 5.2.9. SEM of the fine fraction along the Rambla Honda.

Mineral Assemblage	R. Alias US of Honda	R. Honda	R. Alias DS of Honda
Si, Chl, Micas	23	79	63.5
Feldspar	3	6	7
Fe Oxide/Rutile/Zr	10	8	10
Calcite/Dolomite	43	5	5.5
Other minerals	21	2	14

Table 5.2.1. SEM analysis of samples taken at the Alias/Honda tributary junction, mineral assemblages presented as a percentage of total grain assemblage. Si- quartz, Chl-chlorite, Micas- including biotite and muscovite, Feldspar- Na, Ca and K, Zr-Zircon.

b) The Polopos Sub-Reach

In the Polopos sub-reach three samples where taken for analysis under the Petrological microscope and on the SEM from around the confluence of the Rio Alias and the Rambla de los Feos (tributary junction 2 on figure 5.2.6). Both streams drain Alpujarride and Neogene basin-fill material dominated by calcareous sands throughout this reach. Thin section analysis from the Rio Alias above the Feos junction (Figure 5.2.7) presents a mixed grain assemblage. More than half of the assemblage is characterised by Alpujarride grains and quartz (possibly also of Alpujarride origin) with sandstone and carbonate material dominating the remaining sediment assemblage. Alpujarride schist is represented by the mineral assemblage of quartz, chlorite and micas and can be clearly identified on both the petrological thin sections and on the SEM (Figure 5.2.7, Figure 5.2.11 A-C and Figure 5.2.12). Figure 5.2.10 presents compositional analysis produced using the SEM of the common schist minerals i.e. quartz (Figure 5.2.10 A), chlorite (Figure 5.2.10 B) and muscovite (Figure 5.2.10 C). SEM analysis identifies a grain assemblage characterised by Alpujarride schist and carbonate material with accessory minerals present including: pyrite, apatite, hornblende, rutile and kaolinite.

On the Rambla de los Feos the grain assemblage indicated by the petrological analysis is similar to that of the Rio Alias, with a high proportion of Alpujarrride schist grains present (Figure 5.2.7). However there is a higher proportion of sandstone represented in the grain assemblage on the Feos (27%), relative to the Rio Alias (Table 5.2.2) and the mineral assemblage presented on the SEM suggests that this sandstone is sourced from the calcareous sandstone, as the number of carbonate grains is high. This is consistent with ground outcrop as the lower Feos drains a large area of calcareous sandstone upstream of the junction with the Rio Alias.

Downstream of the confluence on the Rio Alias, the grain assemblage is very similar to that presented on the Rio Alias upstream of the Feos junction (Figure 5.2.7), a mixed grain assemblage dominated by Alpujarride schist and quartz grains. The proportion of sandstone has decreased to just 16 % downstream of the Feos junction whilst the proportion of carbonate material is similar to the Rio Alias above the Feos junction at 26%. The Rambla de los Feos had a smaller proportion of carbonate material than the Rio Alias and a higher proportion of sandstone. Downstream of the tributary junction the relative proportion of sandstone decreases and the carbonate

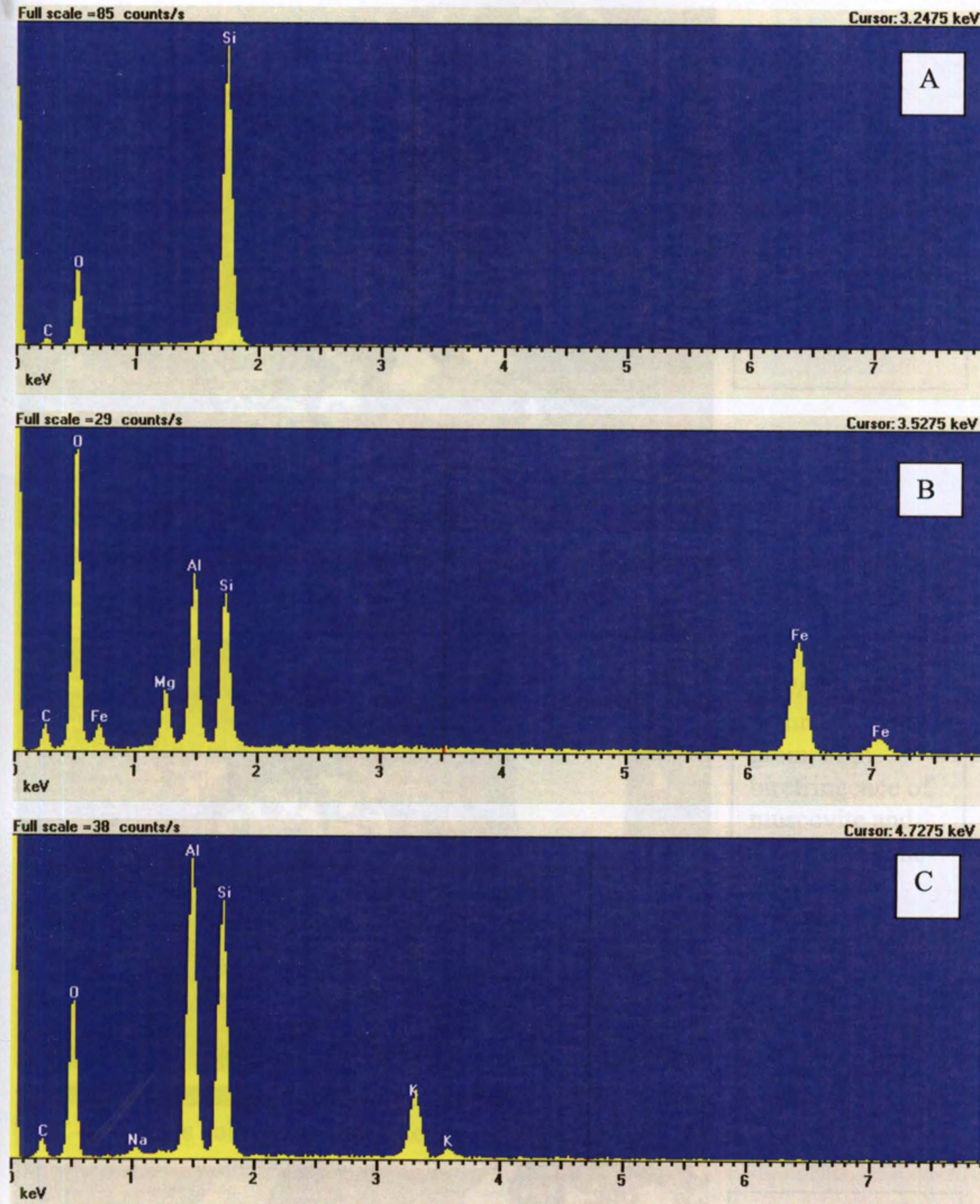
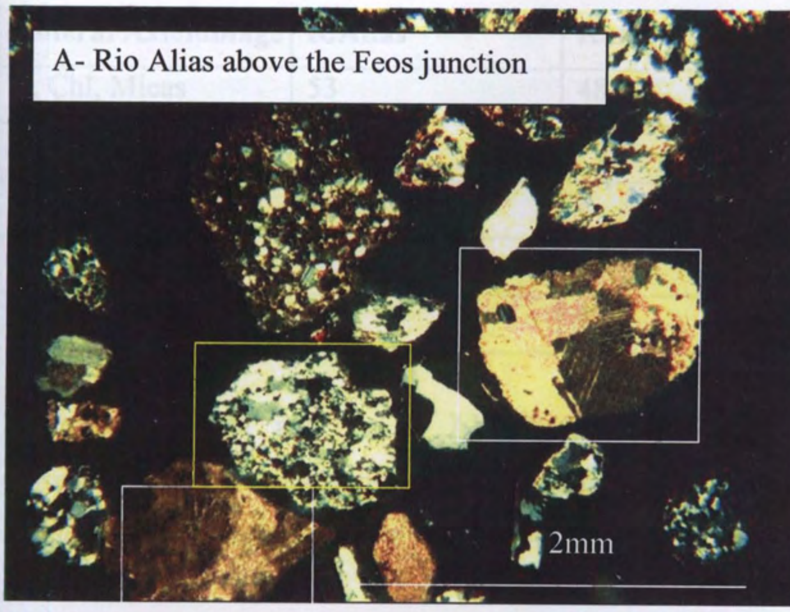
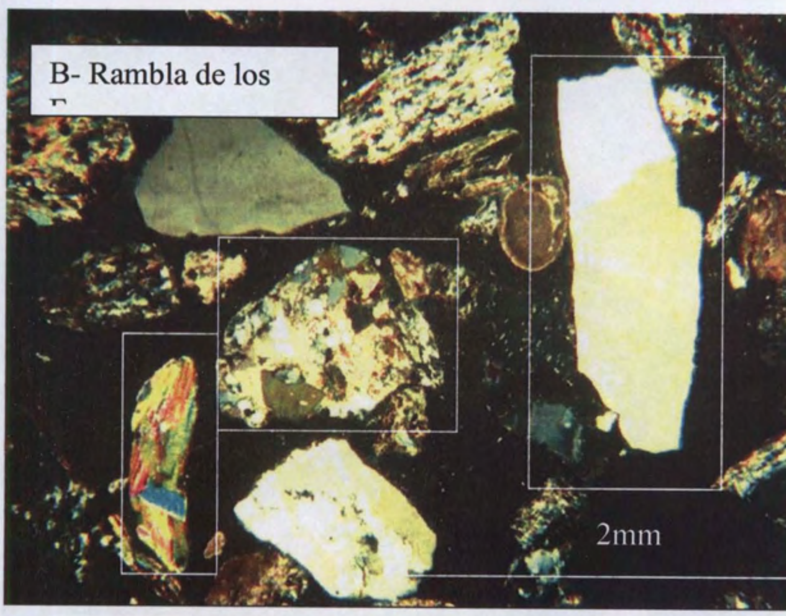


Figure 5.2.10 A-C. Compositional analysis of the main constituents of the Alpujarride low-grade schist: A) quartz, B) chlorite and C) muscovite.



NB// Well developed calcite crystals (white boxes) and poly-crystalline quartz (yellow box).



NB// Undulose nature of quartz grain, high birefringence of muscovite and lithic sandstone grain (white boxes).

NB// High density of opaque minerals in schist grain (yellow box) and well developed crystals of muscovite (white boxes).

Figure 5.2.11 A-C. Thin section analysis: location as in Figure 5.2.6/7.

Mineral Assemblage	R.Alias	Rambla de los Feos	DS of confluence
Si, Chl, Micas	53	48	51
Feldspar	11	6	15
Fe Oxide/Rutile/Zr	11	8	9
Calcite/Dolomite	18	34	20
Other minerals	7	4	5

Table 5.2.2. SEM analysis of Alias/Feos tributary junction, mineral assemblages presented as a percentage of total grain assemblage. Si- quartz, Chl- chlorite, Micas- including biotite and muscovite, Feldspar- Na, Ca and K, Zr-Zircon.

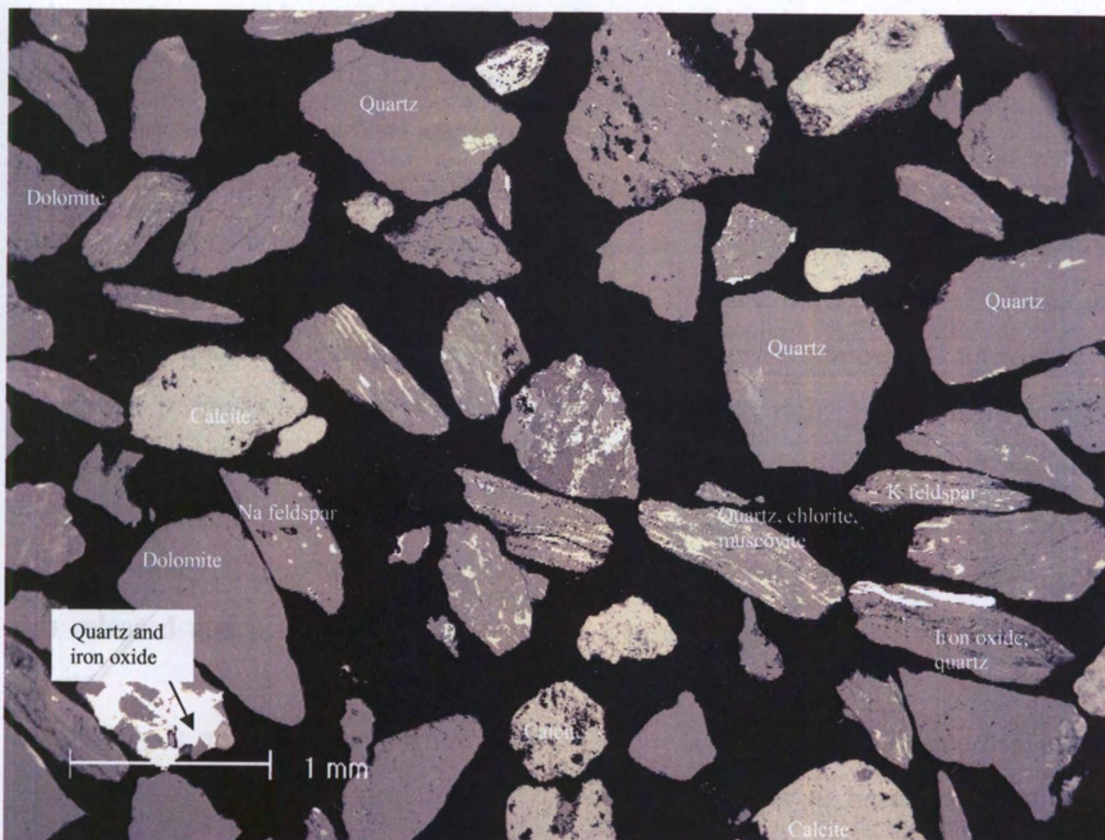


Figure 5.2.12. SEM of the fine fraction on the modern channel along the modern Rio Alias downstream of the Feos junction.

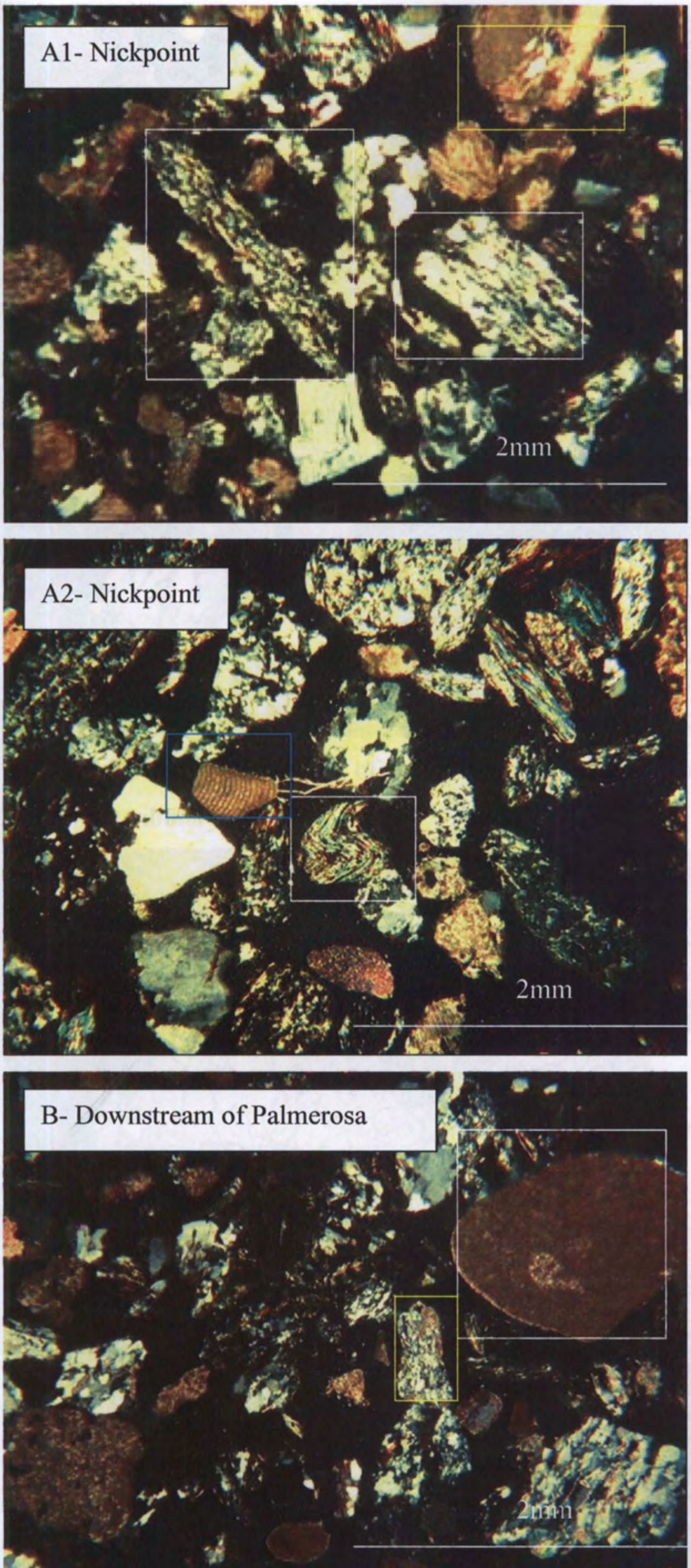
increases. Therefore the grain assemblage suggests that the Rio Alias downstream of the confluence is receiving more sediment from upstream on the Alias than from the Feos. SEM analysis suggests the grain assemblage is dominated by Alpujarride schists, similar to that upstream on the Rio Alias. Minerals such as titanium, rutile, apatite, hornblende and kaolinite suggest input from the metamorphic rocks of the Alpujarride unit.

c) The Argamason Sub-Reach

In the Argamason sub-reach two samples were taken for petrological grain analysis at the head of the basin at the modern nickpoint and downstream of the Palmerosa tributary at the eastern edge of the basin (see red and blue stars on Figure 5.2.6). The sample taken at the downstream limit of the sub-reach also underwent analysis on the SEM. At the nickpoint the assemblage of grains is mixed, quartz and carbonate grains dominating the assemblage (combined total proportion 62%). The remaining 38% is evenly distributed between the Alpujarride schists and sandstone.

At the distal end of the sub-reach, the assemblage changes slightly with a decrease in the amount of sandstone and unknown lithic grains (Figure 5.2.7). The proportion of Alpujarride schist has also increased to constitute almost a third of the grain assemblage (27%). The decrease in the proportion of sandstone is somewhat surprising as a significant proportion of the source area is sandstone rich. However, the volcanic complex is within the source area of the lower portions of the sub-reach and may be responsible for introducing increased proportions of quartz. Furthermore, the increase in carbonate material may be produced by the weathering of the volcanic material; calcium ions released and combining with available oxygen to produce both pure calcite and micrite.

SEM analysis on the lower portion of the system (i.e. DS of the Palmerosa tributary: Figure 5.2.14) revealed almost half of the observed grains to be characteristic of the Alpujarride mineral assemblage (47.5%). A large proportion of the sample was of single quartz grains. However, feldspathic and carbonate grains made up for c.40% of the assemblage. The volcanic complex is a calk-alkaline deposit, and the increase in carbonate/feldspathic and quartz minerals may record the input of newly eroded, and weathered, volcanic lithics (Figure 5.2.14 B).



NB// Schist grains containing opaque minerals (white boxes) and micritic carbonate (yellow box).

NB// Characteristic crenulation cleavage within schist grain (white box) and shell fragment (blue box).

NB// Micritic carbonate grain (white box) and lithic grains (yellow box).

Figure 5.2.13 A/B. Thin section analysis: location as in Figure 5.2.6/7.

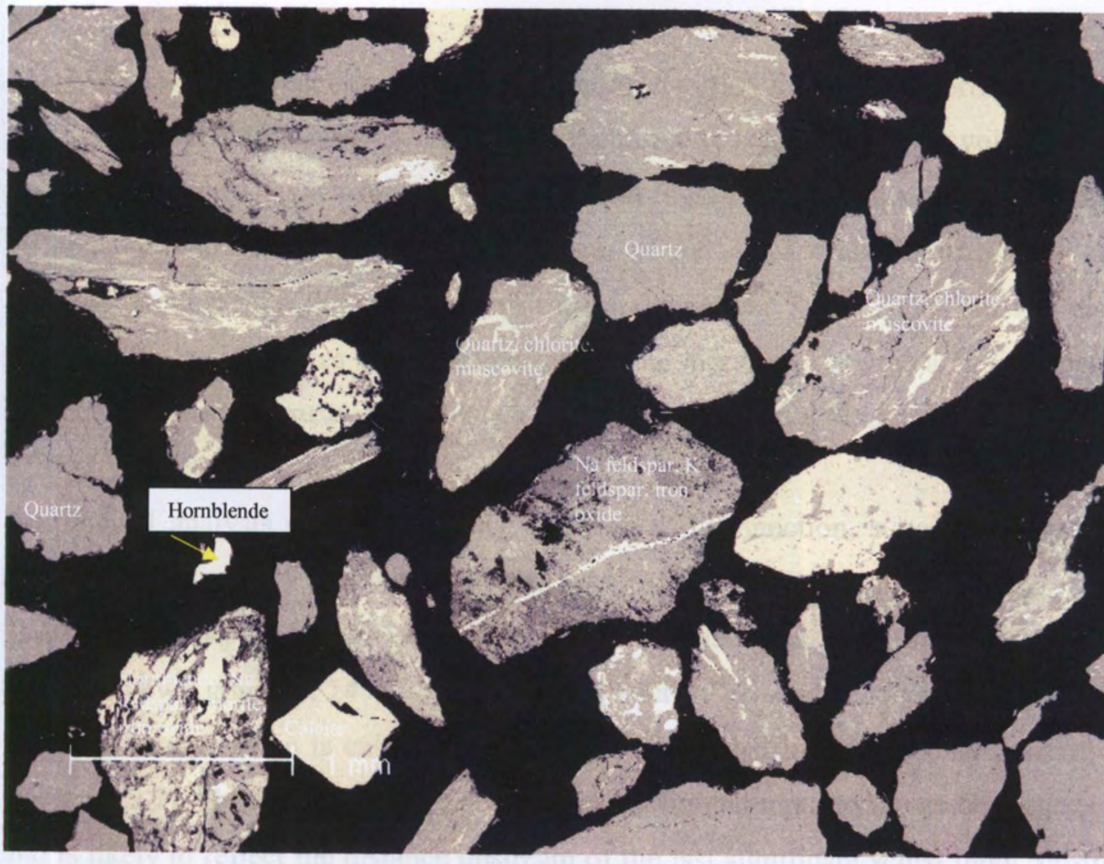


Figure 5.2.14 A. SEM image of modern channels sediments downstream (DS) of the Palmerosa tributary.

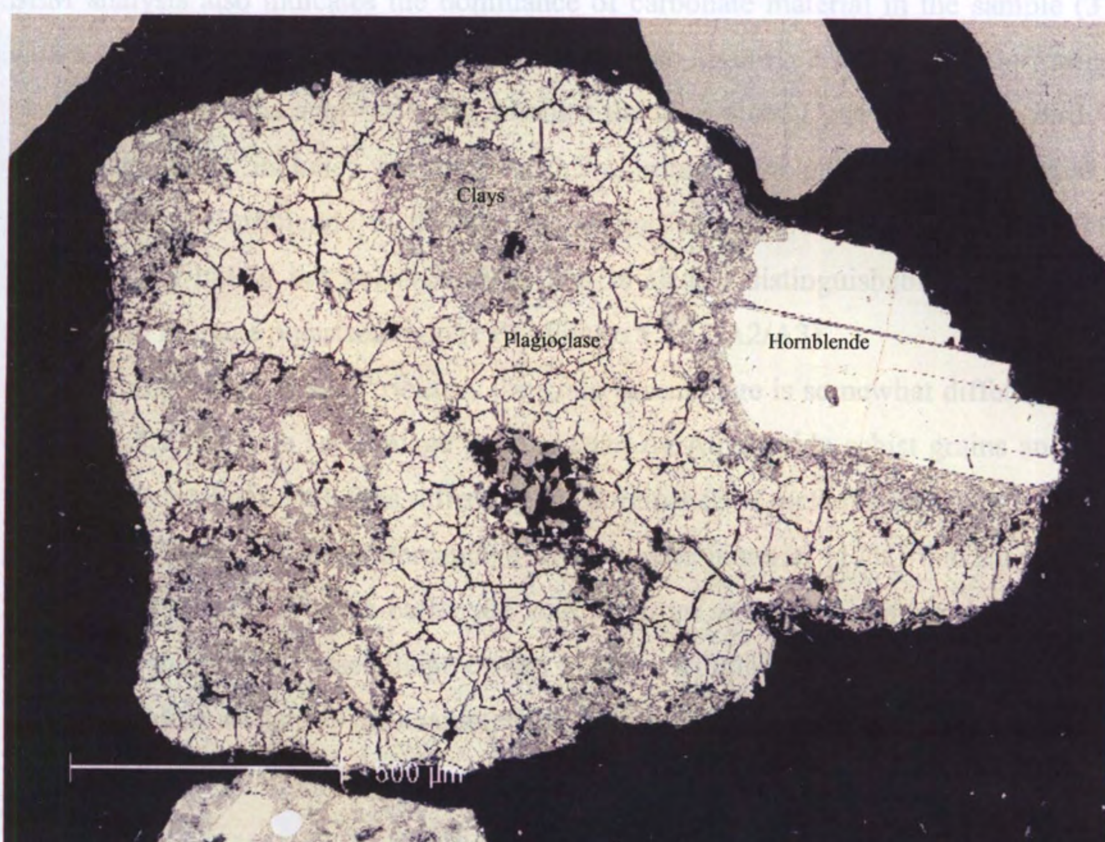


Figure 5.2.14 B. SEM of possible (?) volcanic lithic grain.

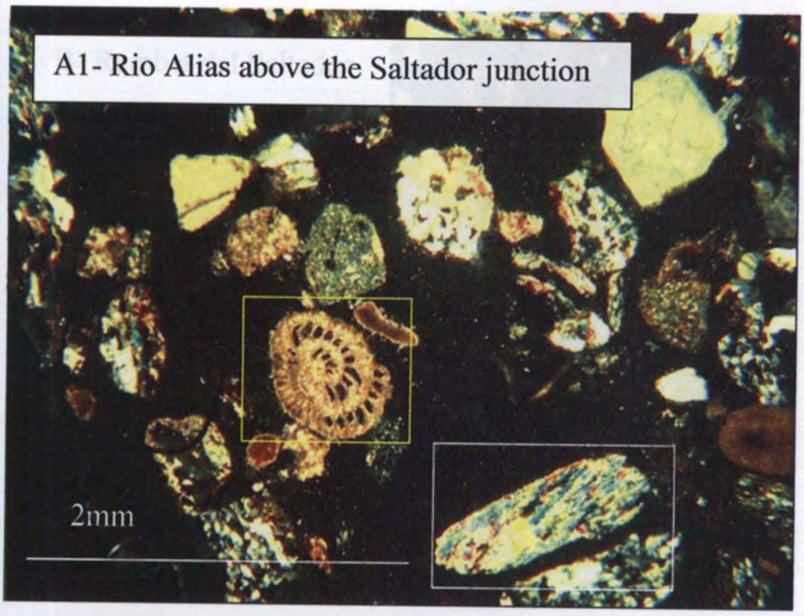
d) The El Saltador Sub-Reach

The El Saltador sub-reach is developed in the most varied lithological portion of the Rio Alias, the source area characterised by metamorphic, sedimentary and volcanic rocks. The Rambla del Saltador tributary (junction 3 on Figure 5.2.6) drains an area dominated by metamorphic rocks, whilst the main stem of the Alias drains metamorphic rocks upstream (reflected in the sediments of tributary junctions 2 and 3) and in this coastal portion, clastic sandstones and volcanic rocks. The mixture of source area lithologies is reflected in the sediment assemblages around the Saltador/Alias confluence (Figure 5.2.7).

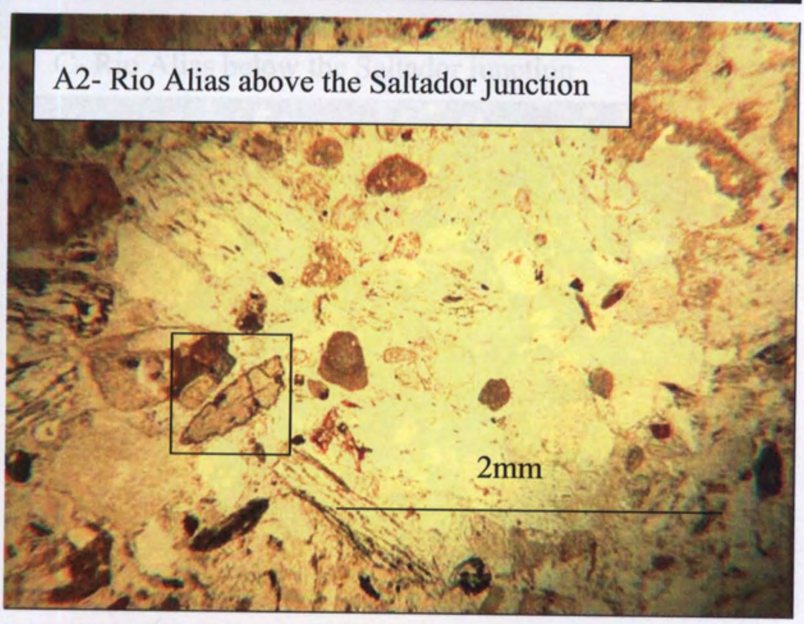
Petrological analysis of the sediments upstream of the junction, suggest a very mixed assemblage of grains, carbonate material dominating the sediment assemblage (32%). The proportion of hornblende grains has increased as has the proportion of other/unknown grains at 14% (to be discussed later). The sandstone proportion is small, however the sandstone is calcareous and may be recorded in the carbonate assemblage (Figure 5.2.7). The Alpujarride schist material has limited input to the assemblage (18%) and is likely to reflect the distance upstream of the last significant schist input, upstream of the nickpoint in the Argamason sub-reach (Figure 5.2.7).

SEM analysis also indicates the dominance of carbonate material in the sample (37%), with a significant amount of *other* minerals (see also Figure 5.2.15). The "other" minerals identified in the SEM analysis differ amongst the three sites. Upstream of the confluence "other" minerals include; hornblende-15.5%, others (including pyrite, olivine and anorthite)-2%. Hornblende in this coastal portion of the system is not sourced in the metamorphic, but in the volcanic rocks and is clearly distinguishable in thin section-particularly in plane polarised light (PPL: Figure 5.2.15 A2/A3).

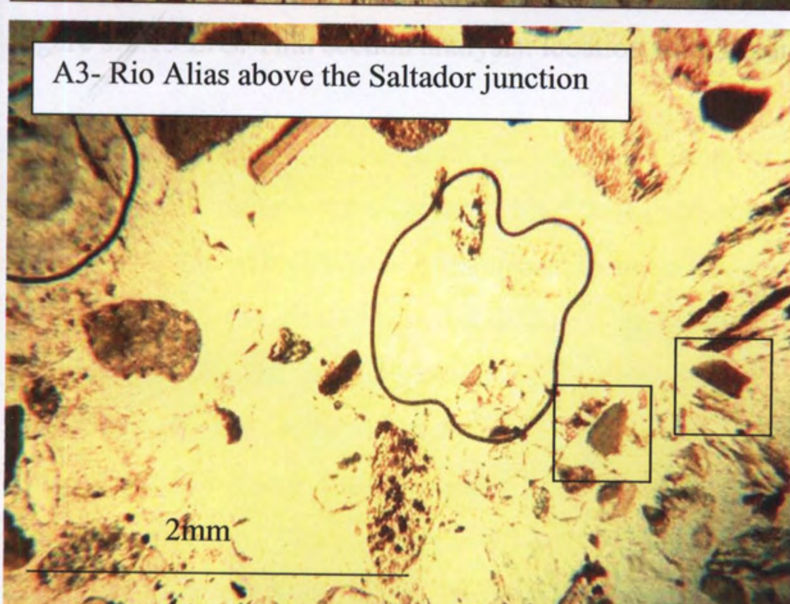
On the Rambla del Saltador tributary the grain assemblage is somewhat different (Figure 5.2.7 and 5.2.15). The assemblage is dominated by Alpujarride schist grains and quartz (cumulative total of 68%), thus reflecting the dominance of metamorphic rocks within the catchment. There is a small percentage of carbonate material (17%) that may relate to basin-fill carbonates or meta-carbonate sourced from within the Alpujarride unit. SEM analysis of the mineral assemblage on the Saltador tributary further suggests dominance of Alpujarride material, by the characteristic quartz, chlorite, mica grain count and by the



NB// Muscovite dominated grain (white box) shell fragment (yellow box).

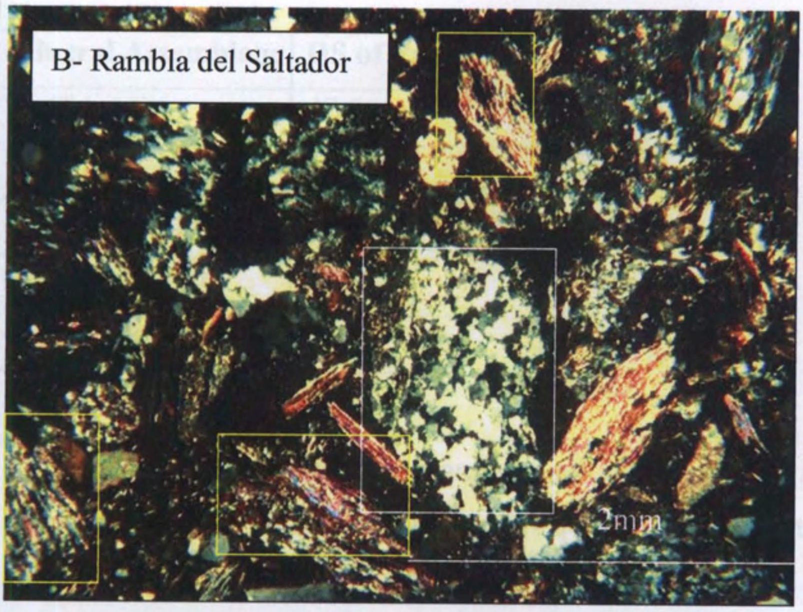


NB// Garnet (black box) with characteristic high relief in Plane Polarised Light (PPL) and isotropy in XPL (cross polarised light: not shown).

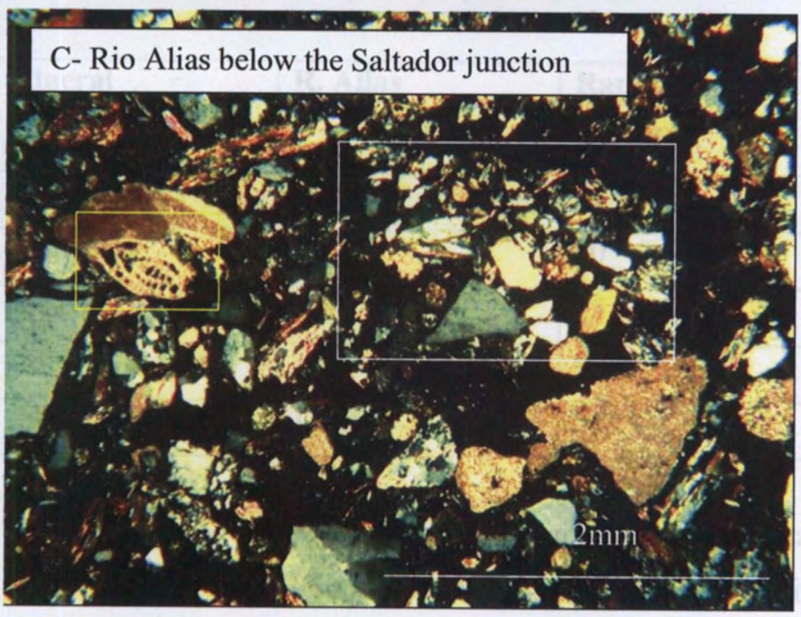


NB// Euhedral hornblende crystals (black boxes) in PPL.

Figure 5.2.15 A1-A3. Thin section analysis: location as in Figure 5.2.6/7.



NB// Dominance of Alpujarride minerals, poly-crystalline quartz (white box) and muscovite (yellow boxes).



NB// Fine grained nature of sediments (white box) shell fragment (yellow box).

Figure 5.2.15 B/C. Thin section analysis: location as in Figure 5.2.6/7.

Mineral Assemblage	DS of Palmerosa
Si, Chl, Micas	47.5
Feldspar	16.25
Fe Oxide/Rutile/Zr	5
Calcite/Dolomite	25
Other minerals	6.25

Table 5.2.3. SEM analysis of Argamason sub-reach, mineral assemblages presented as a percentage of total grain assemblage. Si- quartz, Chl- chlorite, Micas- including biotite and muscovite, Feldspar- Na, Ca and K, Zr-Zircon.

Mineral Assemblage	R. Alias	Rambla del Saltador	DS of confluence
Si, Chl, Micas	28	54	50
Feldspar	7.5	10	10
Fe Oxide/Rutile/Zr	10	25	10.5
Calcite/Dolomite	37	8	16.5
Other minerals	17.5*	3	13

Table 5.2.4. SEM analysis of the El Saltador sub-reach, mineral assemblages presented as a percentage of total grain assemblage. Si- quartz, Chl- chlorite, Micas- including biotite and muscovite, Feldspar- Na, Ca and K, Zr-Zircon. * see text.

high proportion of opaque minerals (including iron-oxides and heavy minerals) sourced from within the metamorphic units (Table 5.2.4).Furthermore there is a lower proportion of carbonate minerals (8%) and other minerals, including hornblende (3%).

Downstream of the confluence the different grain assemblages of the two adjoining systems are reflected in the grain/mineral compositions (Figure 5.2.15 C and Table 5.2.4). Petrological analysis records a lower proportion of Alpujarride schist (37%) relative to the Saltador tributary and a higher proportion of carbonate, hornblende and other grains (38%). The proportion of quartz delivered into the system is slightly less than in the upstream Saltador. The grain assemblage suggests a mixed assemblage fed

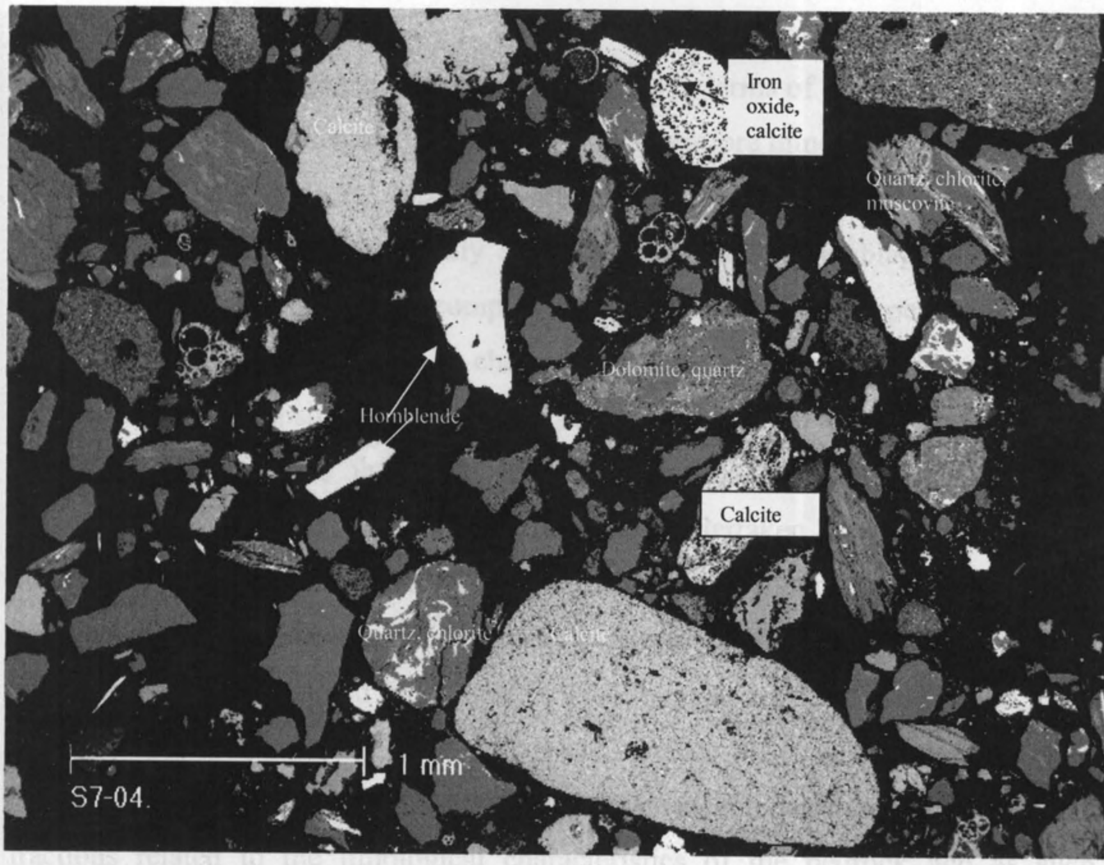


Figure 5.2.16. SEM image of the Rio Alias modern stream, prior to the R. del Saltador tributary.

from both the Alias and the Saltador; however the sediment input from the Saltador appears to dominate the sediment assemblage downstream of the confluence.

SEM analysis also suggests the sample is dominated by the input of Alpujarride material (50%) however the relative amounts of carbonate and hornblende grains have increased relative to those in the Saltador tributary (table 5.2.4). The increase in the carbonate/hornblende component (relative to the Rambla del Satlador) is likely to reflect input from both the Rio Alias from above the tributary junction, and the direct input from the hillslopes downstream of the confluence where the bedrock comprises volcanic and sandstone material.

5.2.3.3 Magnetic Analysis

Magnetic analysis would produce optimum results in terms of a provenance signal, when source area characteristics are lithologically, and therefore mineralogically, characteristic. For this reason magnetic analysis of the modern channel is performed in two ways: firstly for areas providing a lithologically significant sediment assemblage (i.e. the Rambla Honda- draining the Alpujarride complex only), detailed analysis is performed. Secondly, where the sediment assemblage is characterised by a very mixed sediment source-area (i.e. the Rio Alias upstream of the Feos junction: source area including both Neogene basin-fill sediments and the metamorphic Alpujarride complex), only key magnetic measurements are analysed. This approach was undertaken in order to maximise the possible sediment-source linkages inferred via the magnetic analysis. Samples were analysed on a particle-size basis (for particle size description see Table.5.2.5), and units of measurement are defined in Chapter 3. The drainage area of the Rio Alias contains a complex mixture of lithological materials and as such the magnetic signal generated is complicated. Consequently the magnetic signal is concentrated into different particle size fractions related to the lithological characteristics of the bedrock and as such, the magnetic measurements are analysed on a particle-size basis.

a) The Lucainena Sub-Reach

In the Lucainena sub-reach 5 samples underwent magnetic analysis. Results taken from the headwater streams at Lucainena village and on the Rambla del Penoncillo (see Figure 5.2.6), are shown in Table 5.2.5. Results presented are from the medium sand fraction as examination of the bulk results (for all size fractions) suggests the dominant magnetic signal is carried in the medium sand fraction. χ_{LF} values for the Lucainena village stream are an order of magnitude higher than those of the R. del Penoncillo indicating an increased proportion of ferrimagnetic material. Both systems drain both the Alpujarride complex and Neogene marine sediments, however, Iron mines are located upstream of Lucainena village. SIRM measurements are also an order of magnitude larger on the Lucainena stream relative to the R. del Penoncillo (i.e. 29882.7 – 2210.9 $10^{-5}Am^2 kg^{-1}$). The SIRM measurements further suggest the assemblage is dominated by remenance carrying material. The χ_{LF} and SIRM measurements combined indicate an assemblage dominated by ferrimagnetic material along the Lucainena tributary. The Soft IRM value, indicating the concentration of easily magnetised ferrimagnetic material (i.e. magnetite), is an order of magnitude larger on the Lucainena village stream than on

Description	Grain size (mm)
Bulk	<2mm
Coarse	2-0.5
Medium	0.5-0.25
Fine	0.25-0.0625
Silt	0.0625-0.0039
Clay	0.0039-0.00098

Table 5.2.5. Particle size classification.

	χ_{LF} (10^{-8} m^3 kg^{-1})	SIRM (10^{-5}Am^2 kg^{-1})	HIRM (10^{-5}Am^2 kg^{-1})	Soft IRM (10^{-5} Am^2 kg^{-1})
Rambla del Penoncillo	115.30	2210.9	344.63	830.73
Lucainena village headwater Stream	2475.64	29882.76	606.39	15577.14
Rio Alias- pre-Honda	24.31	650.148	169.82	177.40
Rambla Honda	14.42	129.49	16.275	59.61
Rio Alias- post-Honda junction	63.83	1005.08	103.76	404.88

Table 5.2.6. Magnetic measurements for selected sites along the Rio Alias in the Lucainena sub-reach. All measurements on medium sands. For more detail on Rio Alias-pre-Honda and the Rambla Honda see text and figure 5.2.23/5.2.24.

the R. del Penoncillo (Table 5.2.5). Furthermore, HIRM values are greater at Lucainena village but they are greatly reduced in concentration relative to Soft IRM values, and do not show an order of magnitude difference between the sites.

This suggests that magnetically "hard" (canted-antiferromagnetic) minerals such as hematite and goethite are not significant contributors to the magnetic signal of the Lucainena stream. All results presented for the headwater streams suggests that the signal carried along the Lucainena village tributary is magnetically stronger than that of the R. del Penoncillo and is dominated by ferrimagnetic minerals. Furthermore, the magnetic properties of the Lucainena village tributary are dramatically different from elsewhere in the basin and several orders of magnitude larger than all other results reflecting direct input from the iron mineralization zone.

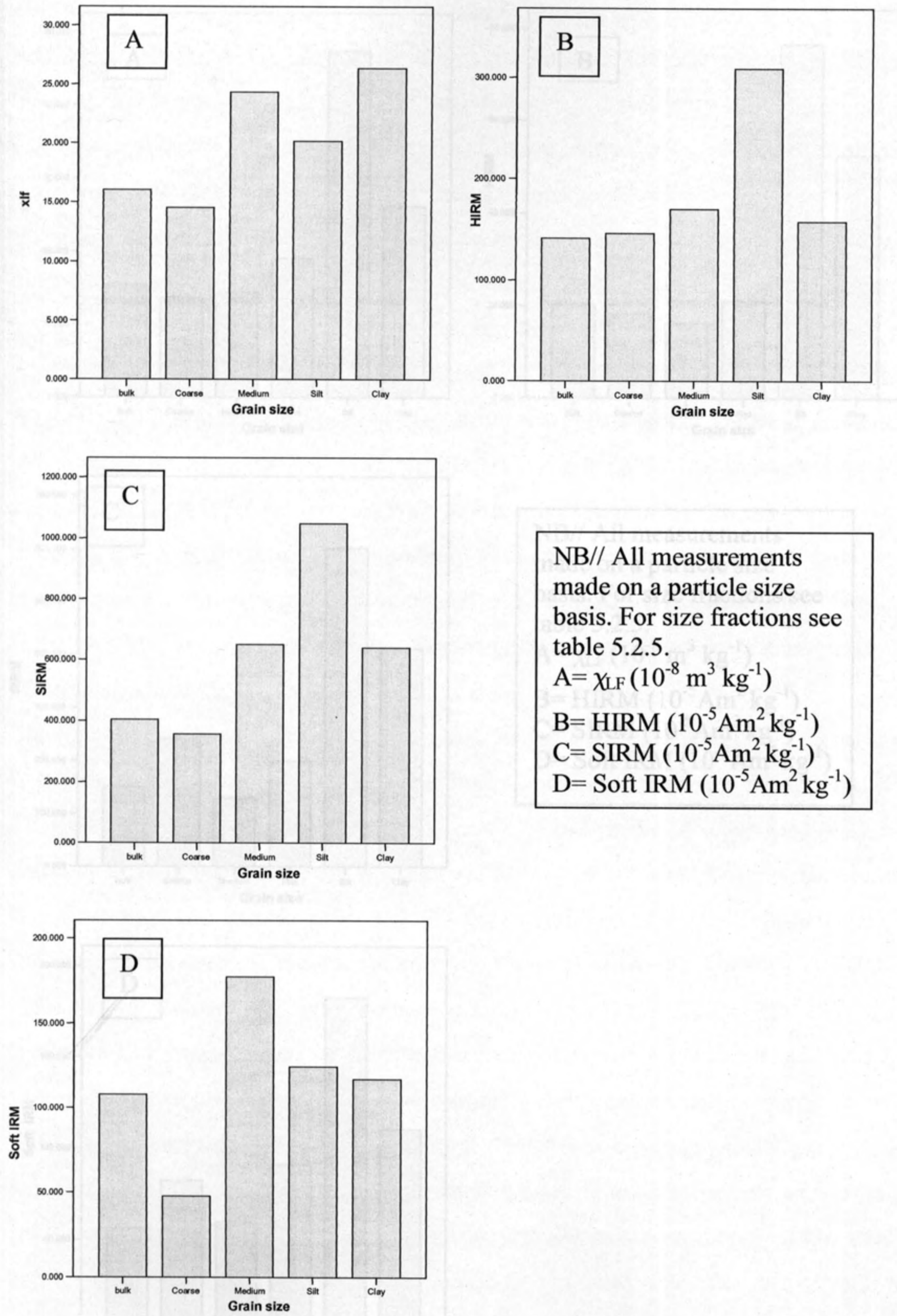


Figure 5.2.17 A-D. Selected magnetic parameters for the Rio Alias above the Honda junction.

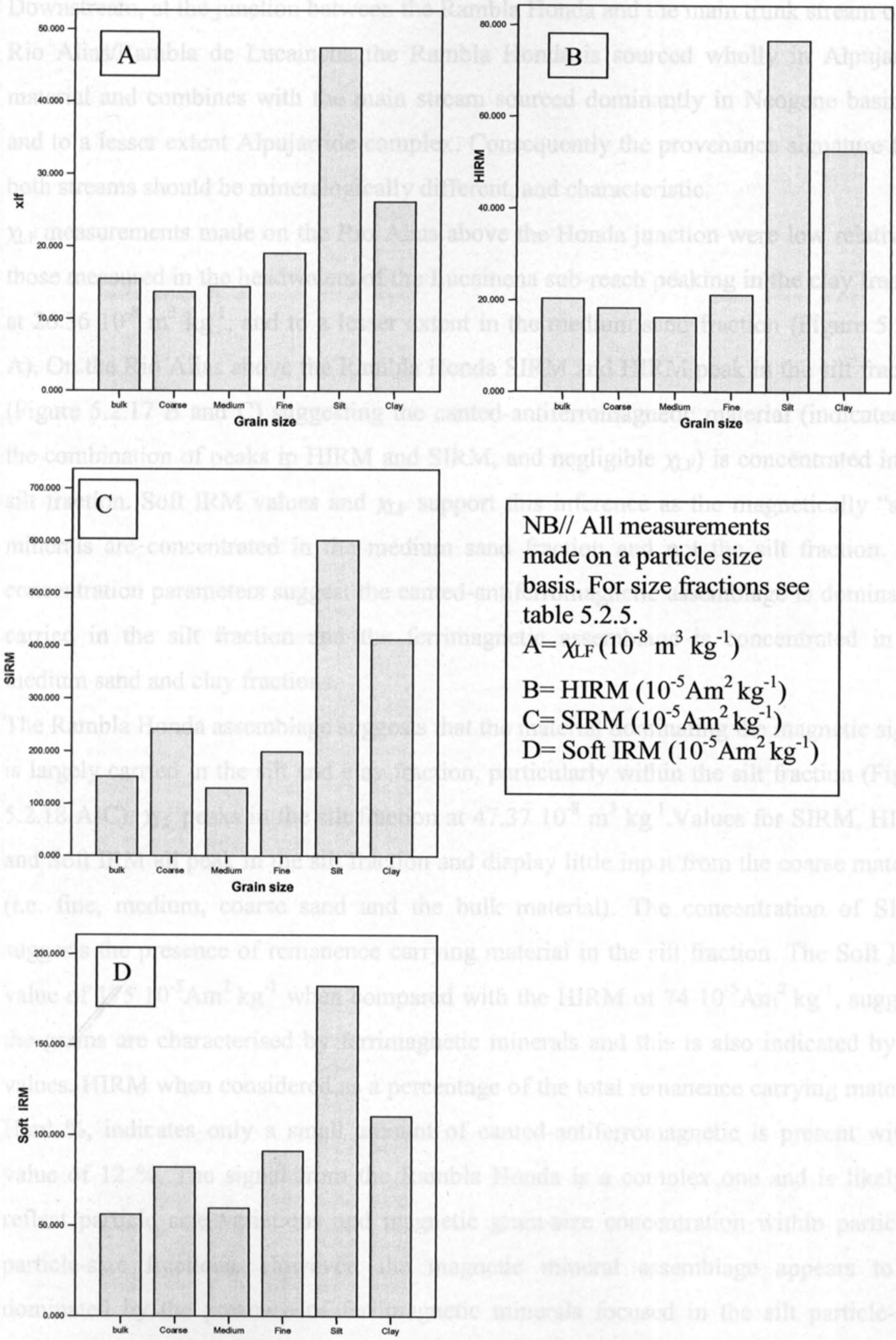


Figure 5.2.18. A-C. Selected magnetic parameters for the Rambla Honda.

Downstream, at the junction between the Rambla Honda and the main trunk stream of the Rio Alias/Rambla de Lucainena the Rambla Honda is sourced wholly in Alpujarride material and combines with the main stream sourced dominantly in Neogene basin fill and to a lesser extent Alpujarride complex. Consequently the provenance signature from both streams should be mineralogically different, and characteristic.

χ_{LF} measurements made on the Rio Alias above the Honda junction were low relative to those measured in the headwaters of the Lucainena sub-reach peaking in the clay fraction at 26.36 10^{-8} m^3 kg^{-1}, and to a lesser extent in the medium sand fraction (Figure 5.2.17 A). On the Rio Alias above the Rambla Honda SIRM and HIRM peak in the silt fraction (Figure 5.2.17 B and C) suggesting the canted-antiferromagnetic material (indicated by the combination of peaks in HIRM and SIRM, and negligible χ_{LF}) is concentrated in the silt fraction. Soft IRM values and χ_{LF} support this inference as the magnetically "soft" minerals are concentrated in the medium sand fraction and not the silt fraction. The concentration parameters suggest the canted-antiferromagnetic assemblage is dominantly carried in the silt fraction and the ferrimagnetic assemblage is concentrated in the medium sand and clay fractions.

The Rambla Honda assemblage suggests that the material dominating the magnetic signal is largely carried in the silt and clay fraction, particularly within the silt fraction (Figure 5.2.18 A-C). χ_{LF} peaks in the silt fraction at 47.37 10^{-8} m^3 kg^{-1}.Values for SIRM, HIRM and Soft IRM all peak in the silt fraction and display little input from the coarse material (i.e. fine, medium, coarse sand and the bulk material). The concentration of SIRM suggests the presence of remanence carrying material in the silt fraction. The Soft IRM value of 175 $10^{-5}Am^2$ kg^{-1} when compared with the HIRM of 74 $10^{-5}Am^2$ kg^{-1}, suggests the grains are characterised by ferrimagnetic minerals and this is also indicated by χ_{LF} values. HIRM when considered as a percentage of the total remanence carrying material, Hard %, indicates only a small amount of canted-antiferromagnetic is present with a value of 12 %. The signal from the Rambla Honda is a complex one and is likely to reflect particle size variations and magnetic grain-size concentration within particular particle-size fractions. However, the magnetic mineral assemblage appears to be dominated by the presence of ferrimagnetic minerals focused in the silt particle-size fraction.

χ_{ARM} analysis presented in Table 5.2.7, demonstrates a clear relationship between particle size and peak χ_{ARM} values (sample mass exhibiting no obvious control over results obtained). χ_{ARM} is related to the concentration of magnetisable (primarily ferrimagnetic) grains in the stable single domain (SSD) range (King et al., 1982), and suggests that on the Rio Alias these grains are concentrated in the clay fraction, whilst on the Rambla Honda they are concentrated in the silt fraction.

The combination of concentration and (magnetic) grain-size indicators suggests the magnetic signal of the Rambla Honda is carried in the silt fraction, and in this fraction the concentration of ferrimagnetic grains is focused within the SSD magnetic grain-size range. It is possible that the small mass of the silt sample (1.05g) means that the signal produced from the ferrimagnetic grains is diluted by canted-antiferromagnetic/paramagnetic/diamagnetic minerals when measuring χ_{LF} on the Bartington MS2 meter. The results from the Rio Alias stream suggest a more complicated relationship as χ_{ARM} is concentrated within the clay fraction whilst SIRM and HIRM parameters peak in the silt and clay fractions and Soft IRM peaks in the medium sand fraction. The Rio Alias system at this point drains mostly basin-fill material and a small amount of the Alpujarride complex, and is likely to reflect a complicated signal produced by the mixing of these sediments and downstream variations in particle grain size.

Sample	**Mass (g)**	**χ_{ARM} (10^{-8} m^3 kg^{-1})**
R. Honda – Silt	1.05	373.97
R.Honda - Clay	5.07	92.33
R. Alias – Silt	1.20	187.00
R. Alias - Clay	1.45	375.29

Table 5.2.7. Magnetic measurements on the silt and clay fraction on the R. Honda and the R. Alias.

Downstream of the junction of the two streams the mineral assemblage should reflect a mixed provenance signal. Table 5.2.6 shows general magnetic parameters and quotients for the Rio Alias downstream of the Honda confluence. An increase in absolute values of χ_{LF} and Soft IRM downstream of the junction, suggests an increase in the concentration of easily magnetised ferrimagnetic minerals – concentrated in the medium sand fraction. SIRM measurements peak at 1005.08 10^{-5}Am^2 kg^{-1} in the medium sand fraction, similar to that of the Rio Alias upstream of the Honda tributary, however upstream the peak value occurs in the silt fraction. The total concentration of remanence carrying minerals indicated by SIRM, appears to be greater on the downstream portion of the Rio Alias than on the Rambla Honda. In the medium sand fraction HIRM measures 103.76 $^{-5}Am^2\ kg^{-1}$, however the peak measurement is within the silt component and measures 199.2 $^{-5}Am^2\ kg^{-1}$. This value is closer to that on the Rio Alias upstream where HIRM also peaks in the silt fraction.

The magnetic measurements suggest a complicated sediment assemblage that contains ferrimagnetic materials that are concentrated within the medium sand particle size range. However, as on the Rio Alias upstream, the proportion of canted-antiferromagnetic material (i.e. hematite and goethite) indicated by HIRM, peaks in the silt fraction. It is suggested that on the main stream below the confluence the mineral assemblage indicated by the magnetic parameters is particle-size dependant. The ferrimagnetic grains (i.e. magnetite) are concentrated within the medium sand fraction whilst the canted-antiferromagnetic minerals (i.e. hematite and goethite) are concentrated in the silt fraction.

b) The Polopos Sub-Reach

The junction of the Rio Alias and the Rambla de los Feos (Figure 5.2.6) in the Polopos sub-reach, is marked by a change in source-area provenance as the Rambla de los Feos drains conglomerates sourced in the Sierra de los Filabres to the north and consequently brings high-grade metamorphics into the system. As has been discussed in Chapter 4.3, prior to the capture event (terraces A-C) the Sorbas basin drainage fed the Rio Alias and consequently a large proportion of high-grade material was fed into the system. Following the capture event (terraces D/E and the modern channel) input of the high-grade metamorphics was from re-working of fluvial conglomerates, consequently limiting the amount of input of high-grade material into the system.

Upstream of the Feos junction the Rio Alias drains an area dominantly of Neogene basin-fill sediments and to a lesser extent of Alpujarride complex. It is therefore similar to the Rio Alias in the Lucainena sub-reach above the Rambla Honda confluence. Table 5.2.8 summarises the general magnetic properties associated with the modern channel. Unlike the headwater sediments in the Lucainena sub-reach, the sample here cannot be generalised by medium sands. χ_{LF} peaks in the medium sand fraction (bulk and fine sand also have similar values), however all other concentration parameters generally contain peaks in the fine sand and silt fractions (Table 5.2.8).

SIRM values, indicating the concentration of all remanence carrying minerals, are consistent throughout the range of particle size fractions and show no real variation with grain size: the fine sand and silt fraction yielding average values for SIRM. HIRM values are an order of magnitude lower than SIRM values and peak in the silt and fine sand fractions. Soft IRM values also peak in the silt and fine sand fraction, and suggest significant contributions from ferrimagnetic minerals within these particle size ranges. The range of concentration parameters analysed suggests that the assemblage has an extremely complex mix of minerals apparently dominated by remanence bearing minerals (as indicated by SIRM values). However, the ferrimagnetic assemblage is concentrated in the silt and fine sand fractions (Soft IRM and χ_{LF} values) and in the medium sand fraction. χ_{LF} values for the silt and clay fractions were not measured, due to the sample size, as silt and clay recovery from the sample was poor (the samples from the Rio Alias < 3g in mass).

The Rambla de los Feos is sourced in a lithologically distinct area and magnetic analysis is presented in Figure 5.2.19 (and to a lesser extent Table 5.2.8). No fine sand material was recovered from the sample to allow analysis on this size fraction. χ_{LF} peaks in the silt and clay fraction, and also in the medium sand fraction. SIRM measurements peak in the silt and medium sand fraction (Figure 5.2.19 B) though all

	χ_{LF} (10^{-8} m^3 kg^{-1})	SIRM (10^{-5}Am^2 kg^{-1})	HIRM (10^{-5}Am^2 kg^{-1})	Soft IRM (10^{-5} Am^2 kg^{-1})
Rio Alias – pre-Feos	47.49 (med)	718.86 587.54	59.63 70.80	342.87 224.28
Rambla de los Feos	27.44 (med)	- 438.30	- 61.56	- 134.61
Rio Alias – post Feos	28.22 (med)	818.66 778.05	109.54 140.35	109.54 140.35

Table 5.2.8. Selected magnetic parameters the Rio Alias up- and downstream of the Feos junction (for location see Figure 5.2.9). χ_{LF} measurements on medium sands. For the others red values relate to the fine sand fraction and the black values relate to the silt fraction. See text for more detailed analysis of the Rambla de los Feos.

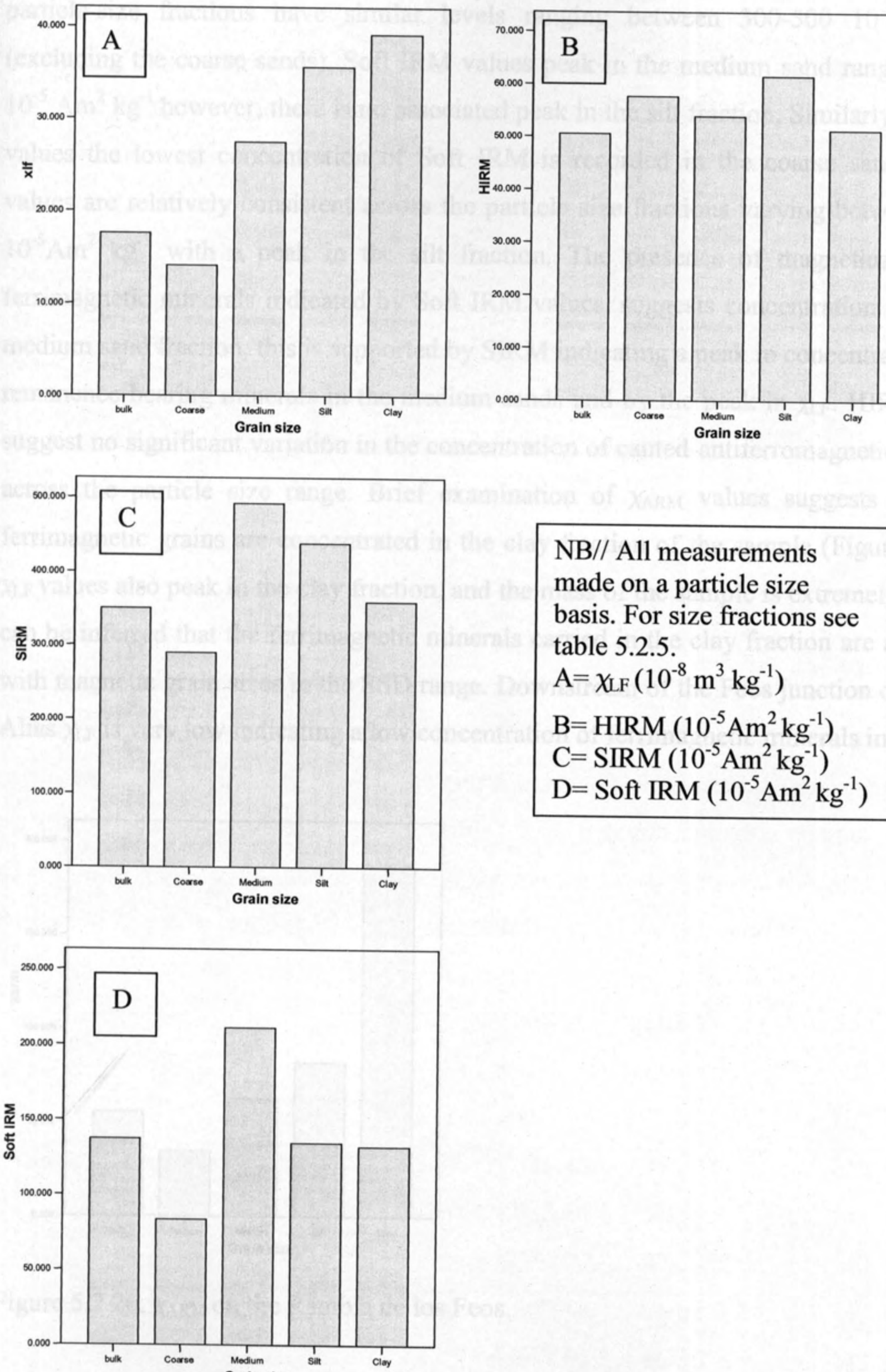


Figure 5.2.19. A-D. Selected magnetic parameters for the Rambla de los Feos.

particle-size fractions have similar levels ranging between 300-500 10^{-5}Am^2 kg^{-1} (excluding the coarse sands). Soft IRM values peak in the medium sand range at c.200 10^{-5} Am^2 kg^{-1} however; there is no associated peak in the silt fraction. Similarly, to SIRM values the lowest concentration of Soft IRM is recorded in the coarse sands. HIRM values are relatively consistent across the particle size fractions varying between 50-60 10^{-5}Am^2 kg^{-1} with a peak in the silt fraction. The presence of magnetically "soft" ferrimagnetic minerals indicated by Soft IRM values, suggests concentration within the medium sand fraction, this is supported by SIRM indicating a peak in concentration of all remanence bearing minerals in the medium sands and by the peak in χ_{LF}. HIRM values suggest no significant variation in the concentration of canted-antiferromagnetic minerals across the particle size range. Brief examination of χ_{ARM} values suggests that SSD ferrimagnetic grains are concentrated in the clay fraction of the sample (Figure 5.2.20). χ_{LF} values also peak in the clay fraction, and the mass of the sample is extremely small. It can be inferred that the ferrimagnetic minerals carried in the clay fraction are associated with magnetic grain sizes in the SSD range. Downstream of the Feos junction on the Rio Alias χ_{LF} is very low indicating a low concentration of ferrimagnetic minerals in the

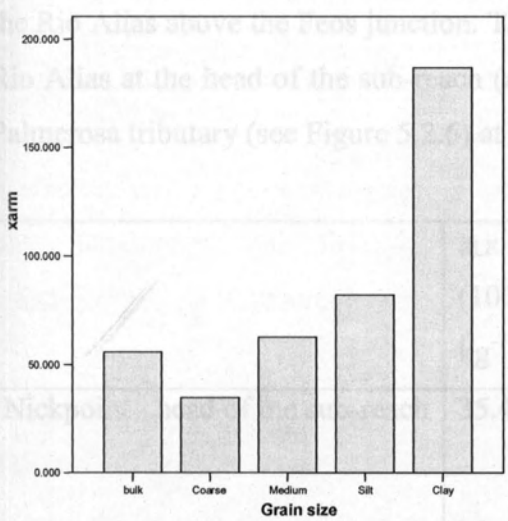


Figure 5.2.20. χ_{ARM} on the Rambla de los Feos.

Sample	Mass (g)
Rambla de los Feos– Silt	0.249
Rambla de los Feos - Clay	0.396

Table 5.2.9. Mass of silt and clay fractions on the Rambla de los Feos.

sample (Table 5.2.8), and also shows a decrease from the Rio Alias upstream of the Feos junction. SIRM measurements however, show a slight increase as do HIRM measurements in both distinctive particle size fractions. Soft IRM results though exhibit a small decrease in concentration. The concentration parameters suggest an increase in the overall concentration in remanence carrying minerals in both the silt and fine sand particle size fractions (relative to the Alias above the Feos). The decrease in Soft IRM coincident with an increase in HIRM values, suggests the proportion of canted-antiferromagnetic minerals has increased and is responsible for the slight increase in the proportion of remanence carrying minerals. Hard % also increases in the fine sands from 8% on the Rio Alias above the confluence to 13% below the confluence and in the silt fraction from 12% to 18%. This further supports the inference of an increase in the canted-antiferromagnetic contribution.

c) The Argamason Sub-Reach

The Argamason sub-reach is located largely in Neogene basin-fill sediments but has tributary systems (i.e. the Gafares) feeding Alpujarride material into the system, consequently the sediment provenance characteristics are somewhat similar to those of the Rio Alias above the Feos junction. Table 5.2.10 lists concentration parameters for the Rio Alias at the head of the sub-reach (at the modern nickpoint) and downstream of the Palmerosa tributary (see Figure 5.2.6) at the distal end of the sub-basin.

	χ_{LF} (10^{-8} m^3 kg^{-1})	SIRM (10^{-5}Am^2 kg^{-1})	HIRM (10^{-5}Am^{2}kg^{-1})	Soft IRM (10^{-5} Am^2 kg^{-1})
Nickpoint - head of the sub-reach	35.48	586.45	75.248	218.22
	-	568.66	99.58	154.62
		674.90	87.55	330.20
Downstream of Palmerosa	69.36	809.14	78.08	347.22
	-	743.44	66.36	248.13
	-	698.50	70.06	279.65

Table 5.2.10. Selected magnetic parameters the Argamason sub-reach- (for location see Figure 5.2.6). Measurements on fine sands (red values), silt fraction (black values) and clay fraction (green values).

Magnetic properties are dominantly carried in the fine sand, silt and clay fractions (Table 5.2.10). χ_{LF} measurements on the fine sand fraction at the head of the sub-reach indicate weak susceptibility in the sample (35.48 10^{-8} m^3 kg^{-1}) suggesting only a small amount of ferrimagnetic material in the sediment assemblage. Downstream, at the distal portion of the system the χ_{LF} measurements show a slight increase to 69.36 10^{-8} m^3 kg^{-1} suggesting a slight increase in the proportion of ferrimagnetic minerals, such as magnetite, within the sediment assemblage. SIRM values also increase downstream in all particle size fractions (Table 5.2.10) indicating a downstream increase in the proportion of remanence carrying minerals in the sample. HIRM displays little variation between the samples suggesting little variation in the concentration of canted-antiferromagnetic minerals in the sediment assemblage through the Argamason sub-reach. However, Hard % decreases between the nickpoint and downstream of the Palmerosa tributary in the fine sands (13-10%), silt (18-9%) and clay (13-10%) indicating a decrease in the proportion of canted-antiferromagnetic minerals. Soft IRM values follow the pattern exhibited by SIRM, increasing downstream in both the fine sand and silt fractions but showing a small decrease in the clay fraction.

The minerals dominating the magnetic assemblage are concentrated in the fine sand, silt and clay fractions in both samples from the sub-reach. Furthermore the magnetic properties suggest an increase in the concentration of ferrimagnetic minerals downstream (represented by increases in χ_{LF} and SIRM) and a small decrease in the concentration of canted-antiferromagnetic material (Hard %). The clay fraction appears not to reflect these changes as sharply as the fine sand and silt fraction, exhibiting a minor increase in SIRM, small decrease in HIRM and an anomalous decrease in Soft IRM values.

d) The El Saltador Sub-Reach

The coastal portion of the Rio Alias is lithologically distinct from the other sub-reachs due to the significant outcrop of calc-alkaline volcanic material. The R. del Saltador tributary is sourced mainly in the Alpujarride complex, but also includes basin-fill sediments and volcanic material. The Rio Alias above the tributary junction with the Rambla del Saltador is currently incising into marine sands and volcanic material, the volcanic material is easily eroded whilst the sandstone is well cemented and fairly resistant to erosion in this reach. χ_{LF} measurements on the Alias above the Saltador junction peak in the fine sand fraction at 283.86 10^{-8} m^3 kg^{-1} (Table 5.2.11) a value almost triple that of the Rio Alias upstream of the volcanic input in the Argamason sub-

	χ_{LF} (10^{-8} m^3 kg^{-1})	SIRM (10^{-5}Am^2 kg^{-1})	HIRM (10^{-5}Am^2 kg^{-1})	Soft IRM (10^{-5} Am^2 kg^{-1})
Rio Alias – above the Saltador	283.86	1773.53	69.822	938.99
	-	822.57	59.23	410.04
	103.26	688.11	41.46	403.21
Rambla del Satador	52.94	444.38	30.40	184.96
	-	394.03	42.82	102.11
	57.64	491.59	33.405	188.74
Rio Alias – below the Saltador	161.08	1228.23	89.928	580.71
	-	807.38	80.130	395.70
	95.76	730.02	54.34	358.86

Table 5.2.11. Selected magnetic parameters the El Saltador sub-reach- (for location see fig. 5.2.9). Measurements on fine sands (red values), silt fraction (black values) and bulk samples (blue values).

basin discussed in the previous section (Table 5.2.10). χ_{LF} varies across the particle size fractions (Figure 5.2.21 A) though no measurements were made on the silt and clay fraction due to the small sample size rendering unreliable values. SIRM and HIRM demonstrate the same pattern of measurement peaks in the fine sand fraction and also in the silt fraction (Figure 5.2.21 B and C). HIRM, indicating the concentration of canted-antiferromagnetic minerals, is however relatively low (c.f. SIRM) and fairly consistent across the particle-size fractions varying between c.30-70 10^{-5}Am^2 kg^{-1}. HIRM as a percentage of SIRM (Hard %) is relatively low ranging between 4 to 6 % across the particle size range on the Rio Alias above the Saltador confluence, also indicating a low concentration of canted-antiferromagnetic minerals. SIRM however is concentrated in the fine sand fraction (peaking at 1773.53 10^{-5}Am^2 kg^{-1}) and to a lesser extent in the silt fraction (Figure 5.2.21 C). This suggests remanence carrying minerals are concentrated in the fine sand fraction in this location. The values of SIRM vary markedly across the particle size range; however all the absolute values are above 300 10^{-5}Am^2 kg^{-1} suggesting significant presence of remanence carrying minerals in all particle-size fractions. Soft IRM values also follow the same pattern as χ_{LF} and SIRM peaking in both the fine sand and silt particle-size ranges (Figure 5.2.21 D), and also in the bulk sample.

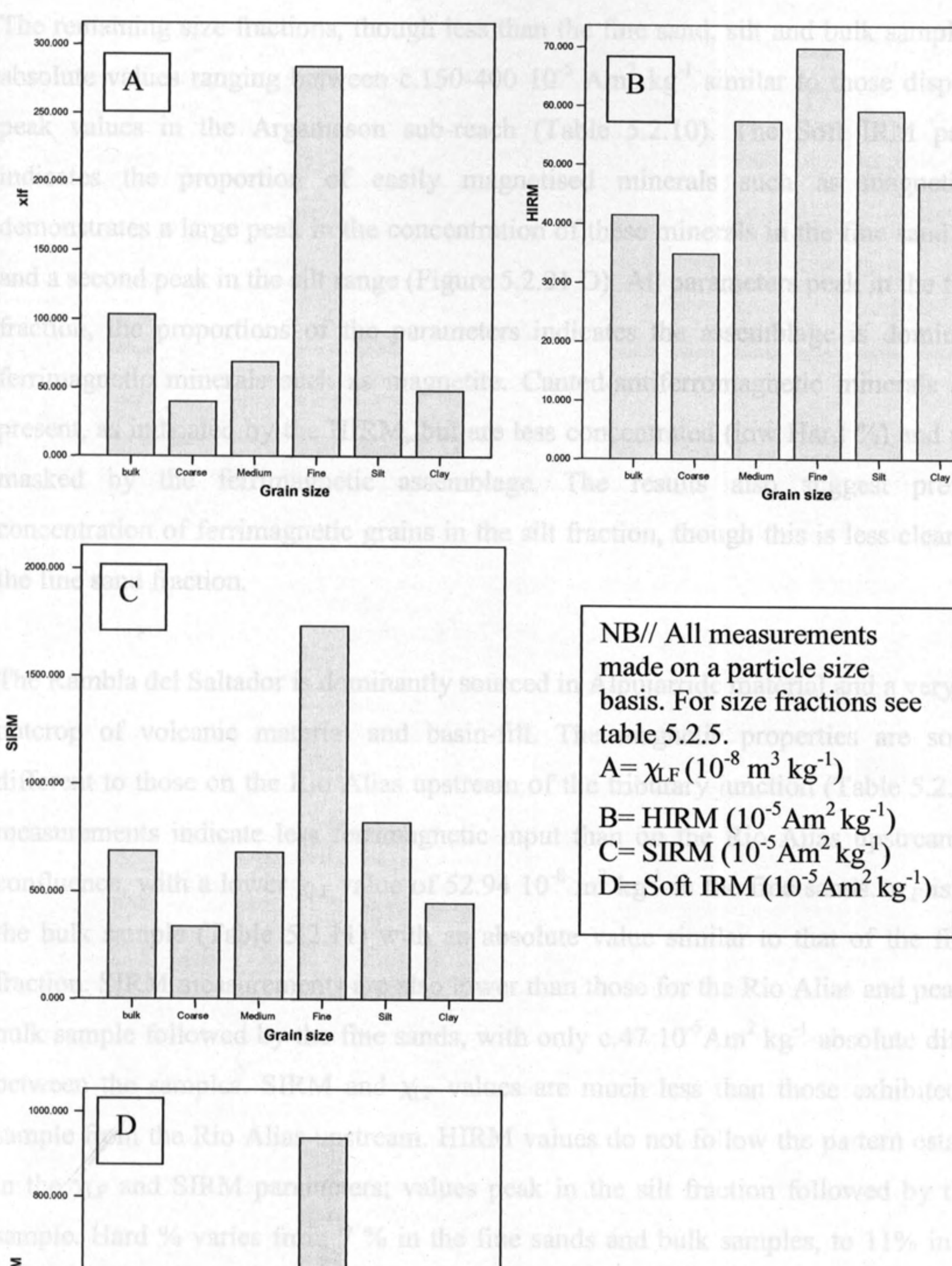


Figure 5.2.21. Selected magnetic parameters for the Rio Alias above the Saltador confluence.

The remaining size fractions, though less than the fine sand, silt and bulk samples, have absolute values ranging between c.150-400 10^{-5} Am^2 kg^{-1} similar to those displayed as peak values in the Argamason sub-reach (Table 5.2.10). The Soft IRM parameter indicates the proportion of easily magnetised minerals such as magnetite, and demonstrates a large peak in the concentration of these minerals in the fine sand fraction and a second peak in the silt range (Figure 5.2.21 D). All parameters peak in the fine sand fraction, the proportions of the parameters indicates the assemblage is dominated by ferrimagnetic minerals such as magnetite. Canted-antiferromagnetic minerals are also present, as indicated by the HIRM, but are less concentrated (low Hard %) and possibly masked by the ferrimagnetic assemblage. The results also suggest preferential concentration of ferrimagnetic grains in the silt fraction, though this is less clear than in the fine sand fraction.

The Rambla del Saltador is dominantly sourced in Alpujarride material and a very limited outcrop of volcanic material and basin-fill. The magnetic properties are somewhat different to those on the Rio Alias upstream of the tributary junction (Table 5.2.11). χ_{LF} measurements indicate less ferrimagnetic input than on the Rio Alias upstream of the confluence, with a lower χ_{LF} value of 52.94 10^{-8} m^3 kg^{-1} in the fine sands. χ_{LF} is high in the bulk sample (Table 5.2.11) with an absolute value similar to that of the fine sand fraction. SIRM measurements are also lower than those for the Rio Alias and peak in the bulk sample followed by the fine sands, with only c.47 $10^{-5}Am^2$ kg^{-1} absolute difference between the samples. SIRM and χ_{LF} values are much less than those exhibited in the sample from the Rio Alias upstream. HIRM values do not follow the pattern established in the χ_{LF} and SIRM parameters; values peak in the silt fraction followed by the bulk sample. Hard % varies from 7 % in the fine sands and bulk samples, to 11% in the silt fraction. The values are slightly lower however, than those for the Rio Alias upstream (Table 5.2.11). Soft IRM results across the particle-size range presented indicate the same particle-size preference as χ_{LF} and SIRM peaking in the bulk sample, followed closely by the fine sand fraction. Again the values are much lower than those recorded upstream on the Rio Alias.

The magnetic parameters suggest the magnetic mineral assemblage is concentrated in the bulk sample and the silt fraction indicated by χ_{LF}, SIRM and Soft IRM parameters and is dominated by ferrimagnetic minerals. The concentration of canted-antiferromagnetic minerals peaks in the silt sample and forms a larger proportion of the mineral assemblage relative to the Rio Alias upstream. Furthermore, the overall magnetic concentration is less than that of the sample upstream on the Rio Alias.

Downstream of the tributary junction the final stretch of the Rio Alias is developed in Neogene basin-fill and volcanic rocks. χ_{LF} values peak in the fine sand fraction and show a decrease from the upstream portion of the river above the Saltador junction (as do the bulk sample values). The χ_{LF} values are however, much higher than those on the Rambla del Saltador (Table 5.2.11). SIRM values also show a decrease relative to the upstream Alias in both the fine sand and silt particle-size fractions but are again double the value of the Rambla del Saltador samples. The bulk sample values however, show a slight increase in SIRM. HIRM displays different behaviour from χ_{LF} and SIRM, increasing in value in the downstream portion of the Rio Alias in the fine sand, silt and bulk samples (Table 5.2.11), values also increasing relative to the Rambla del Saltador. Soft IRM values on the Rio Alias downstream of the Saltador junction peak in the fine sand fraction and all size fractions show a relative decrease from the samples upstream of the Saltador junction and an increase relative to the Rambla del Saltador.

The final portion of the Rio Alias in the El Saltador sub-reach is characterised by a magnetic mineral assemblage concentrated in the fine sand and silt fractions, whilst also well represented in the bulk samples. The combination of concentration parameters suggests the assemblage is dominated by ferrimagnetic minerals indicated by the values associated with χ_{LF}, SIRM and Soft IRM parameters. All size fractions however suggest a decrease in ferrimagnetic mineral concentration relative to the Rio Alias upstream. Increasing HIRM values however suggest an increase in the input of canted-antiferromagnetic minerals in all size fractions, this is further supported by Hard % ranging from 7% (fine sands and bulk) to 10% (silt) of the total SIRM downstream of the confluence.

5.2.3.4 Magnetic Analysis: Basin-wide trends?

The magnetic results presented in Section 5.2.3.3 are to be considered in terms of mineralogy and links with the Petrological analysis in the following section; however it is important to first examine the downstream (basin-wide) trends in magnetic properties of the channel sediments. The magnetic signal in the fine sediment fraction (<2mm) may be expected to exhibit patterns of preferential sorting into particle-size fractions with downstream diminution of the grains. Basin-wide patterns of magnetic variation are

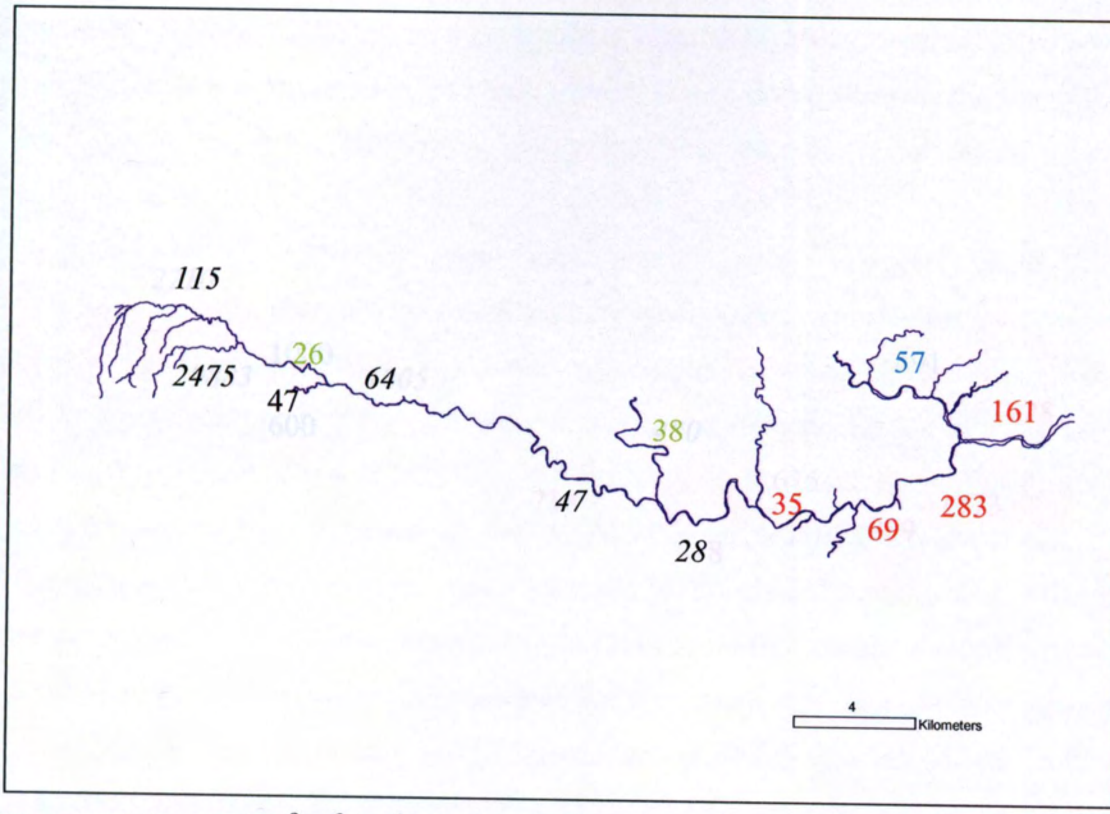


Figure 5.2.22. χ_{LF} (10^{-8} m^3 kg^{-1}) variation along the Rio Alias. Particle size key: Black = silt. Black italic = medium sand. Green = clay. Blue = bulk. Red = fine sand.

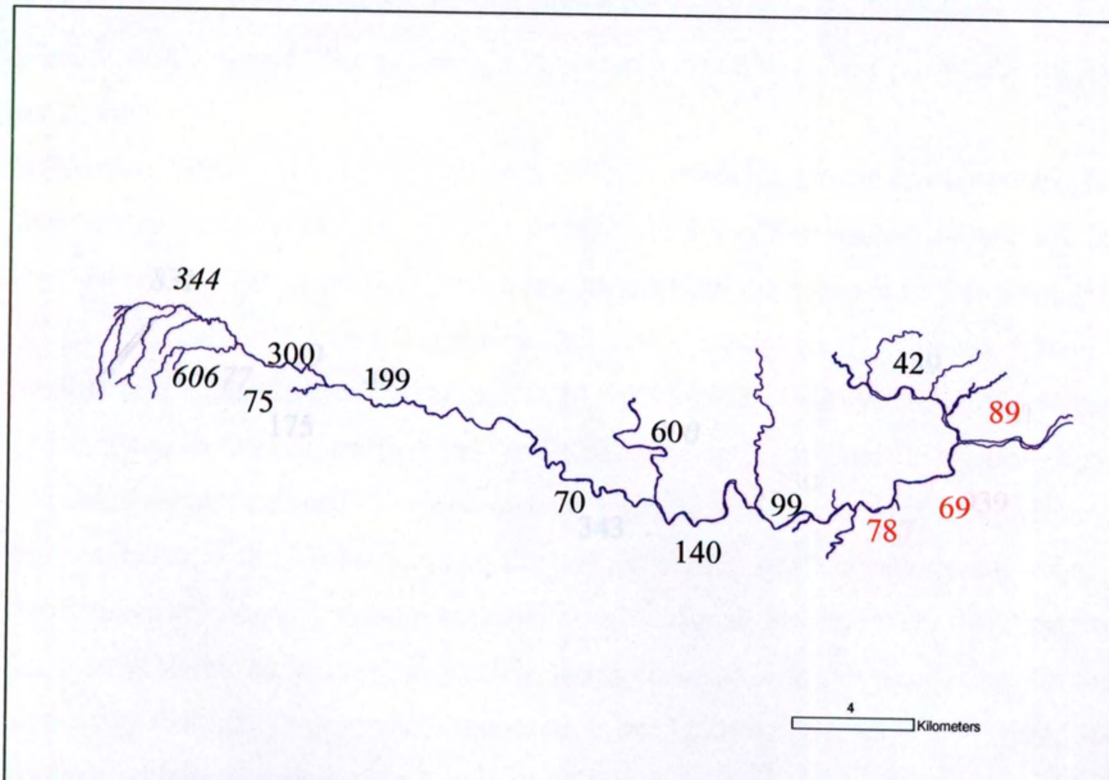


Figure 5.2.23. HIRM (10^{-5}Am^2 kg^{-1}) variation along the Rio Alias (key as Figure 5.2.28).

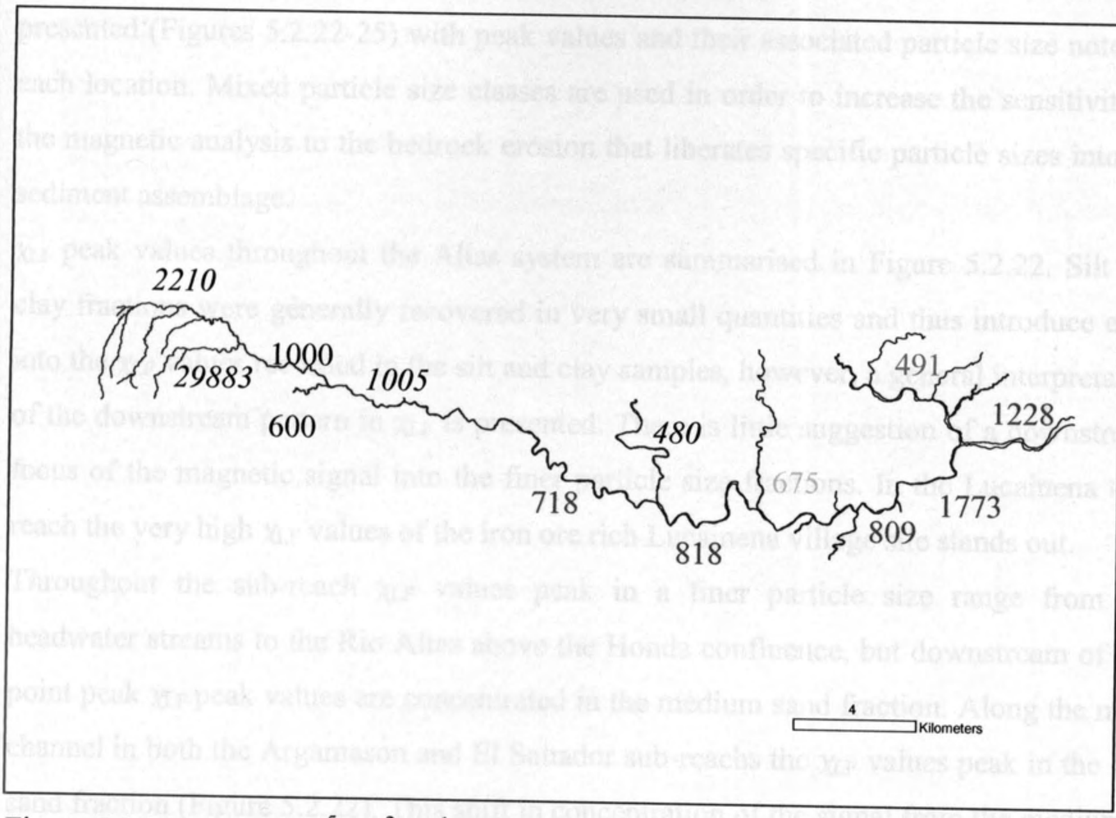


Figure 5.2.24. SIRM (10^{-5} $Am^2 kg^{-1}$) variation along the Rio Alias (key as Figure 5.2.28).

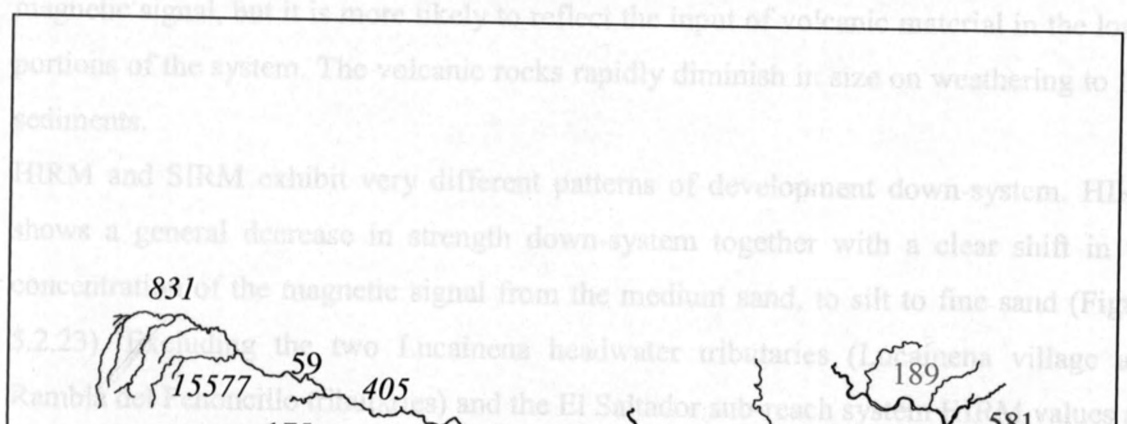


Figure 5.2.25. Soft IRM (10^{-5} Am^2 kg^{-1}) variation along the Rio Alias (key as Figure 5.2.28).

presented (Figures 5.2.22-25) with peak values and their associated particle size noted at each location. Mixed particle size classes are used in order to increase the sensitivity of the magnetic analysis to the bedrock erosion that liberates specific particle sizes into the sediment assemblage.

χ_{LF} peak values throughout the Alias system are summarised in Figure 5.2.22. Silt and clay fractions were generally recovered in very small quantities and thus introduce error into the χ_{LF} values recorded in the silt and clay samples, however, a general interpretation of the downstream pattern in χ_{LF} is presented. There is little suggestion of a downstream focus of the magnetic signal into the finer particle size fractions. In the Lucainena sub-reach the very high χ_{LF} values of the iron ore rich Lucainena village site stands out. Throughout the sub-reach χ_{LF} values peak in a finer particle size range from the headwater streams to the Rio Alias above the Honda confluence, but downstream of this point peak χ_{LF} peak values are concentrated in the medium sand fraction. Along the main channel in both the Argamason and El Saltador sub-reachs the χ_{LF} values peak in the fine sand fraction (Figure 5.2.22). This shift in concentration of the signal from the medium to fine sand fraction may be linked to the downstream diminution of the grains carrying the magnetic signal, but it is more likely to reflect the input of volcanic material in the lower portions of the system. The volcanic rocks rapidly diminish in size on weathering to fine sediments.

HIRM and SIRM exhibit very different patterns of development down-system. HIRM shows a general decrease in strength down-system together with a clear shift in the concentration of the magnetic signal from the medium sand, to silt to fine sand (Figure 5.2.23). Excluding the two Lucainena headwater tributaries (Lucainena village and Rambla del Penoncillo tributaries) and the El Saltador sub-reach system HIRM values are concentrated in the silt fraction. In the El Saltador sub-reach the fine sands carry the dominant magnetic signal. The decrease in grain size of the dominant signal carrying material between the headwaters and the middle portion of the system could relate to a downstream winnowing of the grains carrying the signal. However, the distal portion of the system shows an increase in particle size associated with the peak magnetic signal, suggesting that here downstream diminution is not likely to be responsible. SIRM shows no clear pattern of downstream trends or of decreases in concentration in relation to the particle-size fractions (Figure 5.2.24), all fractions excluding the coarse sands, characterise the dominant signal-carrying material at some location down the system.

Soft IRM values exhibit similar patterns of concentration relative to particle size as HIRM. SIRM is initially concentrated in the medium sand fraction in the headwater reaches of the system, downstream the signal is carried in the silt and medium sand fractions before the Argamason sub-reach (Figure 5.2.25). At the head of the Argamason sub-reach the signal is dominant in the clay fraction, but is quickly replaced by the fine sand fraction downstream in the distal portions of the river system. There is a suggestion of a downstream decrease in the grain size of the material carrying the dominant magnetic signal. However the final portion of the system is again characterised by a magnetic signal carried in the fine sand fraction.

The magnetic parameters when considered on a basin-wide scale, suggest the magnetic signal is generated by the input of local material at each sample site. There are few down-system trends evident in the magnetic signals nor does down-system diminution of the grains significantly impact on the concentration of the magnetic minerals within the particle-size fractions.

5.2.4 Provenance Synthesis on the Modern Channel

5.2.4.1 Introduction

The results presented in Sections 5.2.2 and 5.2.3 are discussed in relation to source area characteristics and therefore patterns of sediment transport. In Chapter 6 the methodological contribution of the techniques employed is appraised and the degree of coherence between the coarse and fine sediment assemblage is assessed.

5.2.4.2 Provenance variation

a) The Lucainena Sub-Reach

Clast analysis in the Lucainena sub-reach suggests that the coarse material supplied to the modern channel is dominated by localised input from the hillslopes and directly from the bedrock material incised by the modern channel. The increased proportion of basin-fill material in the Rambla del Penoncillo (Figure 5.2.5) relative to the Lucainena village stream supports this statement as both streams drain the same source geologies but the Penoncillo incises into a greater area of basin-fill away from the mountain front and consequently records more sandstone and reef limestone. Downstream at the zone of the confluence of the main stream and the tributary Barranco el Campillo, the coarse assemblage is dominated by local input of Alpujarride material (in particular fault rock material) from the northern flanks of the Sierra Alhamilla. The confluence of the main stream and the Rambla Honda marks the first of three major tributary junctions (in terms of lithological signal) along the Rio Alias. Upstream of the confluence basin-fill sandstone and reef limestone is >50% of the coarse sediment assemblage. The assemblage reflects the input of material from the hillslopes of the Sierra Alhamilla and direct incision of the main stream into basin-fill material. The Rambla Honda clast assemblage is dominated by Alpujarride material (the source area is almost completely within the Alpujarride complex), with a small amount of carbonate material - inferred to be sourced from the extensive ground-water calcrete developed on the Rambla Honda. The coarse sediment assemblage downstream of the confluence of the streams is dominated by Alpujarride material and a sub-ordinate supply of carbonate material. Alpujarride material is sourced from both upstream systems and the roundness values presented in Figure 5.2.4 indicate only a very limited increase in mean roundness downstream. However clasts both upstream and downstream of the confluence are similarly classified as sub-rounded. The lack of any clear downstream change in the degree of rounding and the distinct lack of Neogene basin-fill material suggests the material supplied to the main stream below the Honda junction is dominantly sourced from the Rambla Honda and from the adjacent hillslopes – incised into Alpujarride schist. Petrological thin section analysis on the headwater streams of the Lucainena sub-reach suggests subtle differences in the fine sediment load between the Rambla del Penoncillo and the Lucainena village stream (Figure 5.2.7). Both systems have a significant amount of distinct Alpujarride material (i.e. metamorphic schist), quartz and small amounts of sandstone. However the amount of carbonate material differs between the samples. There is a higher proportion of carbonate in the Lucainena village tributary and this is likely to reflect direct incision in to the basin-fill carbonate material, plus the input of meta-carbonate from the flanks of the Sierra Alhamilla. The strike parallel nature of the Lucainena stream and the dominance of meta-carbonate in the Alpujarride unit in this location determines the increase in input to the Lucainena system, relative to the Rambla del Penoncillo. Downstream at the confluence of the Rambla Honda, above the tributary junction the grain assemblage on the main stream is dominated by carbonate material (Figure 5.2.7). The decrease of Alpujarride schist/quartz and the increase of sandstone lithics suggests increasing input from the basin-fill material through which the stream channel is incised.

The subtle variations in supply of fine-grained material suggest an increasingly local input of material above the Honda junction. SEM analysis further supports the indication of a decrease in schist material (relative to the downstream portion of the stream and the Rambla Honda). Dolomite and calcite dominate the grains identified on the SEM and are sourced both from the meta-carbonate and the basin-fill Tortonian calcareous sandstone; thus complicating the interpretation. The fine sediment liberated along the Rambla Honda is dominated by Alpujarride material and quartz, which in this location can be inferred to be sourced from the Alpujarride quartz veins (due to the absence of basin-fill sandstone in the source area). SEM analysis highlights the dominance of the Alpujarride schist grains as indicated by the mineral assemblage of quartz, chlorite and associated micaceous minerals. Downstream of the confluence the fine grain assemblage indicated by the combined petrological thin section/SEM analyses indicates the dominance of Alpujarride material with a small increase in carbonate/sandstone material. Consequently the assemblage is inferred to be dominated by local input from the Rambla Honda and the hillslopes incised into Alpujarride schist, with little input from the main stream above the confluence zone.

Magnetic analysis, similar to the petrological analysis of the fine sediment assemblage, indicates a mineralogical variation between the Lucainena village stream and the Rambla del Penoncillo. Extremely high χ_{LF}, SIRM and Soft values on the Lucainena system are related to the outcrop of a mineralization zone in the Sierra Alhamilla in the hillslopes immediately to the southwest of Lucainena village. The mineralization zone is associated with the iron ore extraction that has now ceased. However, there are spoil heaps remaining, that feed directly into the Lucainena tributary and are consequently supplying highly magnetic materials into the system. The Rambla del Penoncillo drains the same mountain source area as the Lucainena system but χ_{LF}, SIRM and Soft values show no dramatically high values, further supporting the identification of the spoil heaps as the main source of the extremely high magnetic signal. Magnetic properties on the Rambla Lucainena/Rio Alias above the Honda confluence are greatly reduced from those upstream at Lucainena indicating that the magnetic signature at the head of the Lucainena sub-reach is localised and not transported significant distances downstream. Furthermore canted-antiferromagnetic minerals such as haematite and goethite are concentrated in the silt particle-size fraction whilst ferrimagnetic minerals such as magnetite are concentrated in the medium sand and clay fractions. The haematite and goethite minerals are likely to be sourced in the marine basin-fill marls and turbidites and therefore appear to reflect local input. The Rambla Honda magnetic signal is also concentrated in particular particle-size fractions, the silt fraction carrying the dominant magnetic signal. The magnetic assemblage indicates the presence of ferrimagnetic material sourced in the Alpujarride schist, which weathers to fine material rapidly and consequently concentrates the magnetic minerals supplied by the metamorphic material into the silt fraction. Downstream of the confluence of the two streams the magnetic assemblage is complicated. The magnetic signal is partitioned into particle-size fractions: the canted-antiferromagnetic material is carried dominantly in the silt fraction whilst the ferrimagnetic material is focused in the medium sands. However, the input of minerals such as haematite and goethite in the silt fraction and magnetite in the medium sand fraction on the downstream portion of the system, reflect the input of material from the Rambla Lucainena. However the signal is complex as the absolute values indicate an increase in the ferrimagnetic component and a decrease in the canted-antiferromagnetic component. The magnetic signal below the confluence does however, indicate the input of local ferrimagnetic minerals from the schists into the medium sands, whilst the silt fraction is dominated by input from upstream on the Rambla Lucainena (i.e. canted-antiferromagnetic minerals from the marls and turbidites). This may suggest the silt sized grains moving along the main stream are able to persist downstream to mix with the coarser material input from along the Rambla Honda, consequently subtly mixing the signal downstream of the confluence.

The resistance of the bedrock units has a significant control over the range of particle sizes released into the suspended and bedload components of the system. Alpujarride schists and Neogene basin-fill sediments such as sandstones and marls diminish quickly into the fine sediment when transported over short distances. The meta-carbonate and limestone reef material is more resistant to erosion and initially forms coarse clasts. However, the schist material also forms abundant clasts in the coarse assemblage related to localised input, as a large proportion of the drainage area is developed in the Alpujarride schists.

The signal produced by all proxies, indicates the importance of local input of material in both the coarse and fine component in the Lucainena sub-reach.

b) The Polopos Sub-Reach

At the head of the Polopos sub-reach at the village of Polopos the clast assemblage is dominated by Alpujarride schist material with a lesser proportion of carbonate material. The river upstream of this location forms a canyon reach developed in the resistant reef limestone after cutting across the Alpujarride complex of meta-carbonate and schist. The lack of reef limestone material in the assemblage is due to the resistance to weathering of the unit liberating limited amounts of material, and the Alpujaride material consequently dominates the assemblage. The schist material is liberated in abundance just upstream and immediately to the north of Polopos, and so continues to be present in the coarse assemblage. Furthermore, the meta-carbonate of the Alpujarride complex, is relatively resistant to abrasion and is persistent throughout the canyon as large clasts. Two km downstream of Polopos the clast assemblage has changed reflecting the input of local sediments along the channel. Sandstone clasts are now present and the proportion of carbonate clasts has increased, though the Alpujarride complex continues to dominate the assemblage. The channel is incising directly in to Neogene sandstones and limestones but the hillslopes to the north are providing persistently large amounts of the easily erodeable schist material and meta-carbonate. The clast assemblage in the upstream portion of the sub-reach suggests that the input of locally eroded material is dominating the sediment assemblage, and this is further supported by the mean roundness values presented in Figure 5.2.4 (to be discussed below). Downstream above the confluence of the Rambla de los Feos the Alpujarride complex continues to dominate the clast assemblage, however, the proportion of basin-fill clasts has increased, largely due to the increased input of local sandstone. The proportion of Alpujarride material remains constant downstream, reflecting the liberal generation of material from the hillslopes. On the Rambla de los Feos the coarse sediment assemblage is similar to that of the Rio Alias above the confluence, reflecting the similarity of source area. Downstream of the tributary junction the clast assemblage is similar again. The lack of variation (excluding the very small component of hornblende schist introduced from the re-working of Plio-Quaternary conglomerates) in the clast assemblage reflects the similar source areas of the main Rio Alias and the Rambla de los Feos. The schist component is easily generated on the hillslopes and transported into the channel from the southern flanks of the Sierras Alhamilla/Cabrera to the north, and is consequently dominant in the sediment assemblage. Mean roundness (Figure 5.2.4) suggests that much of the schist is likely to be locally sourced and not schist that has been transported from significant distances upstream (i.e. from the Lucainena sub-reach: to be discussed later). The increased proportion of sandstone and carbonate material downsystem is directly related to the incision of the Rio Alias and the Rambla de los Feos into Neogene basin-fill downstream of Polopos. Again, the clast analysis indicates sediment supply dominated by local hillslope input.

Petrological analysis in the Polopos sub-reach was concentrated at the confluence of the Rio Alias and the Rambla de los Feos because of the lack of variation in the source area components in the rest of the sub-reach. On the Rio Alias above the confluence of the Rambla de los Feos the grain assemblage under the petrological microscope indicates a well mixed sediment assemblage with >50% of the assemblage represented by Alpujarride grains and quartz grains. The quartz material is sourced both from the Alpujarride complex and from the Neogene sandstones and consequently cannot be assigned to a particular source lithology. However SEM analysis indicates the Alpujarride complex is dominant within the fine sediment assemblage and consequently it can be inferred that the dominant source of the quartz reflected in the petrological analysis is from Alpujarride vein quartz. The fine sediment supplied to the modern channel thus reflects local input of material dominantly from the Alpujarride complex. The Rio Alias upstream of the Feos confluence incises into limestone material and a small area of calcareous sandstone and this is reflected in the lesser values of these units. On the Rambla de los Feos the grain assemblage is similar but characterised by an increased proportion of sandstone material. The lower portion of the Feos incises into the Cuevas Viejas sandstone, a calcareous sandstone, and this local input of material dominates the fine sediment assemblage. Hornblende from the re-working of pre-capture Plio-Quaternary conglomerates is present in small quantities. The SEM analysis further supports the increased input of local calcareous sandstone with an increase in the proportion of calcite crystals and dolomite grains. The grain assemblages on the Rio Alias and the Rambla de los Feos thus reflect local input and the resistance of source area materials (i.e. reef limestone produces less fine sediment than the Alpujarride schist, whilst the Cuevas Viejas sandstone is quickly dimunited to the fine sediment assemblage). Downstream of the confluence the grain assemblage is similar to that of the Rio Alias upstream of the confluence. A decreasing proportion of sandstone is represented and an increase in the proportion of Alpujarride grains is indicated. Trace quantities of hornblende are also present. SEM analysis further indicates a return to a assemblage similar to that of the Alias upstream, therefore the fine sediment assemblage downstream of the confluence indicates dominant input from along the main channel of the Rio Alias upstream. However, the sediment assemblage along both tributaries is very similar and the absolute contribution of sediment from each feeder cannot be assessed. Perhaps more importantly it can be inferred that once more the grain assemblage indicated by the thin section/SEM analysis suggests a dominance of local sediment supply to the fine sediment fraction.

Magnetic analysis on the fine sediments in the Polopos sub-reach indicates the partitioning of the magnetic signal into discreet particle size fractions. Above the Feos confluence on the Rio Alias the assemblage is dominated by ferrimagnetic minerals such as magnetite, similar to the Rambla Lucainena/Rio Alias above the Honda confluence; the ferrimagnetic minerals may represent input from basin-fill sandstones. The magnetic signal is concentrated into the silt and the fine sand fractions overall. On the Rambla de los Feos the magnetic signal is weaker than that of the Rio Alias and interestingly is carried in a coarser particle size fraction – the medium sands. Overall the magnetic analysis suggests there is less ferrimagnetic material than on the Rio Alias, and, the ferrimagnetic minerals are concentrated in the medium sand fraction (as opposed to the fine sand and silt on the Alias upstream) consequently indicating the Cuevas Viejas as the main source. Downstream on the Alias below the confluence the magnetic analysis indicates an increase in the proportion of remanence carrying material due to an increase in canted-antiferromagnetic minerals (increase in HIRM). This is inferred to be due to the local input of haematite and goethite from the marine marls incised by the Rio Alias downstream of the Feos junction. The magnetic analysis indicates the input of local material is dominating the mineral assemblage particularly on the Rambla de los Feos and the Rio Alias below the confluence. Furthermore the signal is concentrated into particular particle size fractions, possibly related to the weathering characteristics of the source material (i.e. the Cuevas Viejas sandstone producing sand sized material that consequently dominates the magnetic signal along the Rambla de los Feos).

The signals produced by all proxies, indicate the importance of local input of material in the coarse and fine component in the Lucainena sub-reach.

c) The Argamason Sub-Reach

At the head of the sub-reach at the nickpoint the clast assemblage is similar to that downstream of the Feos junction. The main channel is incising into Neogene basin-fill rocks throughout this central portion (downstream of the Feos junction), however the Arroyo Gafares a tributary to the Rio Alias above the nickpoint, incises into Alpujarride material through most of its course and consequently inputs Alpujarride material to the sediment load. Furthermore the basin-fill material is dominated by an unconsolidated sandstone and marl in the central portion of the basin, consequently little material is input into the clast assemblage but goes directly to the fine sediment fraction. The sandstone is variable however, and the nickpoint is formed in more resistant bands of sandstone, and this very local input of coarse material dominates the basin-fill signal, reflecting the direct incision of the stream into these resistant bands of sandstone (liberating coarse clasts). Mean roundness values exhibit no clear downstream rounding, and the clast assemblage present indicates that the coarse load is reflecting relatively local input of material with little indication of long-distance transport of coarse material. Downstream of the Palmerosa tributary the clast assemblage begins to show increased lithological variation with volcanic material and hornblende schist entered into the coarse sediment assemblage. The origin of both clasts is extremely localised to the area of Argamason village. The hornblende schist is re-worked from the abundant alluvial deposits at Argamason village associated with the pre-capture Rio Alias (Maher et al., in press; Maher and Harvey, in press). The volcanic material is sourced from a small outcrop of volcanic rock brought in along the Carboneras Fault Zone that outcrops along the channel at Argamason. The decrease in sandstone and the increase in carbonate material is related to the hillslopes formed in limestone to the north of Argamason, and also to the lack of direct outcrop of sandstone in the channel. The Alpujarride complex continues to dominate the clast assemblage, and this is arguably a local supply of Alpujarride material sourced from the Arroyo Gafares. Downstream, at the eastern-most limit of the sub-reach the clast content exhibits increases in both basin-fill material and volcanic rocks. The channel is incising directly into sandstone and volcanic rocks throughout the last portion of the sub-reach and this is reflected in the clast content.

Petrological analysis was performed on two samples – at the nickpoint (i.e. head of the sub-reach) and the distal portion of the sub-reach in order to encompass the lithological variation through the reach. At the nickpoint the assemblage is mixed, quartz and carbonate grains dominating the assemblage whilst sandstone lithics and Alpujarride grains make up the remaining c.40% of the assemblage. The quartz is sourced in both the basin-fill sandstone and the Alpujarride material; however the large proportion of carbonate material suggests derivation from the sandstone and marl. Furthermore it is likely that a large proportion of the quartz is also derived from the sandstone. The fine sediment fraction therefore indicates direct input from local material, dominating the sediment assemblage. Downstream at the distal end of the sub-reach the fine sediment assemblage has changed slightly from that upstream with an increase in the proportion of Alpujarride material. Furthermore the proportion of quartz increases as does the carbonate material. The increase in Alpujarride material, supported also by the SEM analysis is surprising and may relate to fine sediment transport through the system from the Gafares tributary at the head of the sub-reach (the last input of Alpujarride material). The increase in quartz and carbonate is inferred to reflect the outcrop of volcanic rocks supplying quartz and carbonate/micrite through weathering of the calc-alkaline volcanics. The grain assemblage differs slightly from the fine sediment assemblage presented elsewhere as the assemblage is not dominated by local input. Local input is indicated by the quartz and carbonate material, and the presence of unidentified lithic fragments, but the high proportion of Alpujarride material (both on the petrological section and on the SEM) suggests the fine material is sourced from upstream of the nickpoint.

Magnetic analysis generally indicates an increase in the amount of ferrimagnetic material downstream, and the magnetic properties, as elsewhere along the Rio Alias are concentrated into particular particle-size fractions. The magnetic properties indicate the input of local volcanic material at the distal portion of the system (the increase in χ_{LF} and

SIRM) rather than the downstream transport of Alpujarride material. The different sediment-source linkages inferred by the magnetic and thin section analysis may also reflect the concentration of volcanic grains into particular size fractions.

In the Argamason sub-reach local input is indicated throughout most of the system in both the coarse and fine sediment loads. However in the distal portion of the system the fine sediment fraction indicates a complicated sediment assemblage with both local input, and, long-distance transport from the Arroyo Gafares. It is inferred that the complex grain assemblage is related to the generation of grains from the volcanic rocks concentrating into discrete particle-size fractions.

d) The El Saltador Sub-Reach

The Rio Alias above the Saltador junction (in the El Saltador sub-reach) is characterised by a large influx of volcanic material in the coarse sediment assemblage. The volcanic clasts dominate the sediment assemblage along the Rio Alias in this location. The modern channel is incising directly into the volcanic rocks throughout the majority of this reach upstream of the Saltador confluence, with the Cuevas Viejas sandstone representing only a very minor component of the bedrock channel. The hillslopes surrounding the channel are also composed of volcanic rock. The clast assemblage reflects the immediate source area of the volcanic material as once the material is transported over short distances it quickly diminishes into the fine sediment fraction, due to its weak lithological characteristics. The signal from the Rambla del Saltador is very different from the Rio Alias reflecting the dominant source area of the stream; located in the Alpujarride complex of the Sierra Cabrera. In the final stretch of the Saltador tributary the stream incises through limestones and volcanic rocks introducing limited amounts of those materials into the coarse sediment assemblage. The clast assemblage below the confluence is dominated by the input of Alpujarride material from the Rambla del Saltador, a third of the assemblage is represented by basin-fill and volcanic rocks. The volcanic material is likely to be from adjacent hillslopes, whilst the sandstone and carbonate has been transported downstream by the Rio Alias. Downstream, at the mouth of the river the clast assemblage increasingly reflects direct input from the slopes adjacent to the channel; volcanic rocks and sandstone forming the hillslopes of the coastal stretch of the system. The volcanic rocks outcrop over a greater area than the sandstone, thus the abundance of sandstone clasts relative to volcanic clasts suggests diminution of the volcanic material.

The grain assemblage indicated by petrological thin section and SEM analysis exhibits variation through the El Saltador sub-reach, related to the input of varied lithological units along the coastal stretch of the Rio Alias. Contribution from the Alpujarride complex is minimal and the assemblage is dominated by carbonate, quartz and unknown grains with a significant contribution of hornblende grains. The assemblage indicates local input of carbonate material and volcanic material recorded in the "other" category. Quartz and carbonate (due to weathering of the volcanics) will also be sourced from the volcanic rocks. SEM analysis indicates a high proportion of carbonate material (i.e. micrite) and a significant proportion of hornblende crystals (within the other materials). The hornblende crystals in this location are not sourced in the metamorphic schists, but are sourced from the volcanic material and are easily identified (Figure 5.2.15 A2/A3). The sandstone in this area is calcareous and is likely to contribute to the carbonate signal. The provenance signal indicated by the fine sediment fraction above the confluence indicates the dominance of local sediment input to the modern channel. On the Rambla del Saltador Alpujarride and quartz grains dominate the grain assemblage, sourced from the Sierra Cabrera. A small amount of carbonate and other material relates to the outcrop of the volcanic rocks and basin-fill sediments in the lower portion of the Rambla del Saltador. SEM analysis further supports the inference of the dominant supply of Alpujarride material in the Sierra Cabrera. Below the confluence the grain assemblage indicates a mixture of sediment supplied from the Rambla del Saltador and the Rio Alias. The Alpujarride grains dominate the assemblage and thus suggest a dominance in supply of material from the Rambla del Saltador. The increase in hornblende grains indicates direct input from the slopes adjacent to the modern channel. SEM analysis indicates the dominance of Alpujarride material in the sample, however the other minerals identified including hornblende, suggest input of material not significant upstream on the Rambla del Saltador. The grain assemblage in the El Saltador sub-reach indicates the dominance of sediment supply from local bedrock units.

Magnetic analysis on the Rio Alias upstream and downstream of the confluence and on the Rambla del Saltador, generate signals that can be broadly considered to reflect the input of volcanic grains. On the Rio Alias ferrimagnetic material dominates the magnetic mineral assemblage and is concentrated in the fine sand particle-size fraction. The signal is inferred to relate to the rapid input of volcanic grains into the fine sediment fraction (due to the weathering characteristics). The signal generated on the Rambla del Saltador is somewhat different from that of the Rio Alias above the confluence. Ferrimagnetic minerals dominate the signal though the magnetic minerals are concentrated in the bulk and silt fractions, and the overall magnetic signal is lower than that of the Alias. Downstream of the confluence the magnetic signal is similar to that of the Rio Alias upstream, concentrated in the fine sand fraction and indicating an assemblage dominated by ferrimagnetic minerals (i.e. magnetite). The absolute values are lower than those of the Alias upstream but more than double those of the Rambla del Saltador. An increase in the abundance of canted-antiferromagnetic minerals is also indicated. The magnetic signal generated above and below the confluence is dominated by the local input of volcanic material, however the mixed assemblage of the Rambla del Saltador dilutes the signal slightly suggesting fine sediment input from both adjacent hillslopes (i.e. volcanic material) and from the Rambla del Saltador (Alpujarride grains). Magnetic analysis suggests the dominance of input of local material on the Rio Alias main stream, however the ferrimagnetic signal generated by the volcanic material would mask any other signal generated by the input of less strongly magnetic material (e.g. quartz, gypsum, calcium-carbonate), and therefore may not indicate the quantitative dominance of volcanic material.

Both coarse and fine sediment analysis indicates the dominance of local sediment supply through the system, however, the resistance of the bedrock material to mechanical breakdown also controls the liberation of sediment into the coarse or fine sediment load.

Across the drainage basin of the Rio Alias mean roundness and mean TND values on the coarse sediment assemblage provide little evidence of downstream diminution of the clasts. There is a slight increase in roundness values from the headwaters to the coast but this is a very slight increase and is not reflected in the particle size characteristics recorded (i.e. mean TND). If significant amounts of coarse material supplied to the system were being transported through the system from the headwaters to the coast then a downstream decrease in particle size and an increase in roundness would be expected. Therefore the results presented along the Rio Alias do not appear to be related to long-distance transportation of the coarse material, but rather to localised input of coarse material. Particle size and shape data considered with the lithological data indicate the dominance of local sediment supply in both the coarse and fine sediment loads. Magnetic properties when considered on a basin-wide scale do not indicate long distance provenance characteristics, but local sediment generation controling the magnetic characteristics of the sediment. There are shortcomings in the approach outlined here, generally related to the concentration of both lithological and mineralogical characteristics into discreet particle-size fractions, and this point will be discussed in Chapter 6. However the proxies used all point towards the dominance of local sediment supply controlling patterns of sediment provenance in both the coarse and fine sediment assemblages.

5.3 The Terrace Sequence

5.3.1 Introduction

Analysis of the provenance characteristics of the terrace sequence is dependant upon preservation of the fluvial deposits, accessibility of sections and, for the <2mm fraction, the degree of cementation of the deposit. Where possible, the fluvial deposits associated with the terrace sequence have been analysed in terms of both the coarse clasts, representing the bedload and the matrix or fine sediment representing the suspended load. Clast lithological analysis of the coarse sediment load, and mineral magnetic analysis of the fine (<2mm) sediment load has been completed on the fluvial sediments preserved in all sub-reachs of the Rio Alias.

5.3.2 Bedload

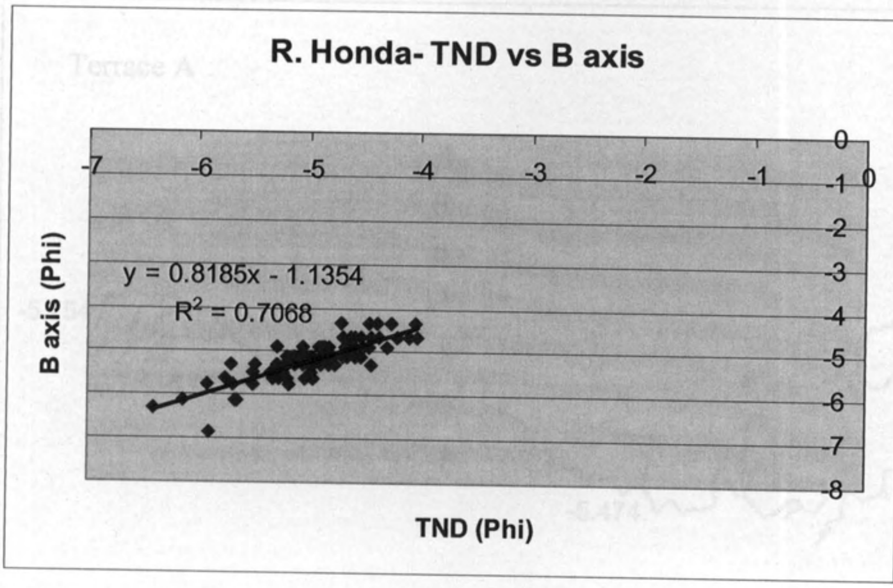
5.3.2.1 Introduction

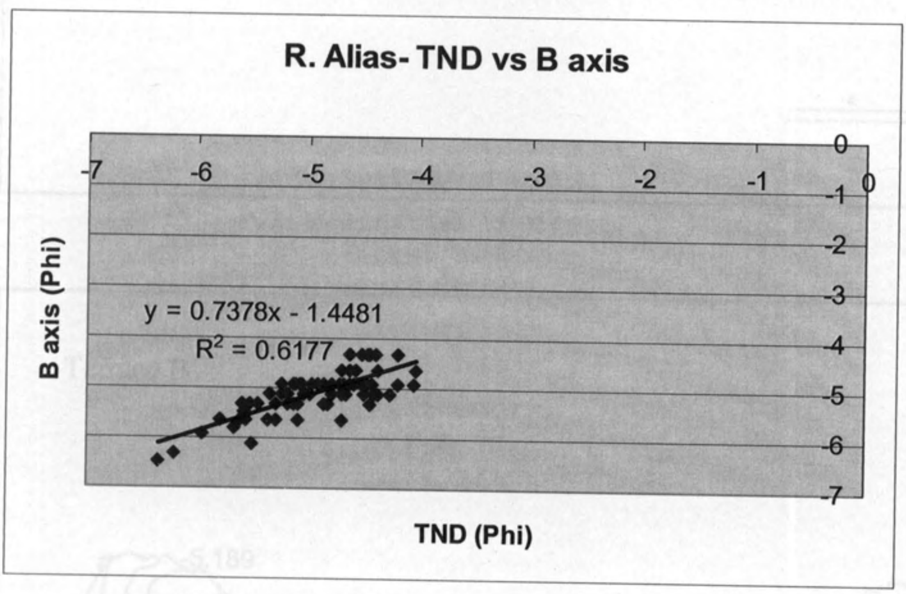
Clast analysis was performed on preserved terrace deposits across the drainage basin. Preservation of the older terrace units across the basin is limited and as such data presented for the older terrace units (A and B) is scarce compared with those for the younger terraces in the sequence (C, D and E). Similarly to the modern channel, and where preservation permits, clast analysis was performed on the sediments associated with significant changes in source area lithology and at tributary junctions.

5.3.2.2 Particle size and shape variation

Analysis of the particle size and shape variations within the terrace assemblage was performed by field descriptions of the degree of roundness and the length of the clast B axis. In order to optimise the time available in the field to cover as many sites as possible B axis only were measured, rather than A, B, C axis, as had been done on the modern channel. Preliminary investigations into the correlation between B axis and TND suggested the B axis measurement was significantly similar to the TND (Figure 5.3.1) to justify measurement of the B axis alone.

Particle size and roundness characteristics are presented in Figure 5.3.2 and 5.3.3 for the Alias drainage basin during each terrace stage. Terrace stage A shows little variation downstream in mean B axis, however, there is a downstream trend in the degree of roundness (using the nomenclature presented in section 5.2.2.2); terrace A is characterised by sub-angular clasts in the Lucainena area and rounded clasts at the coast. Terrace stage B exhibits no evidence of downstream fining in the mean B axis from the





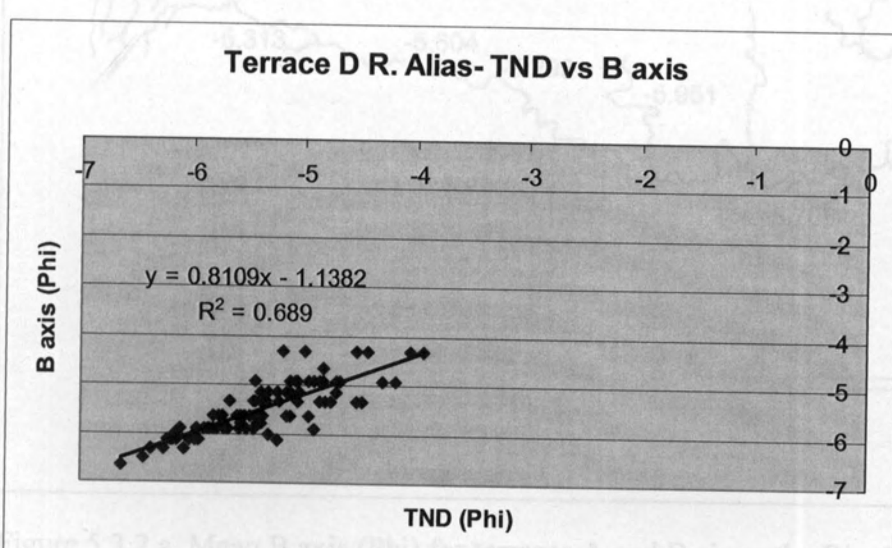
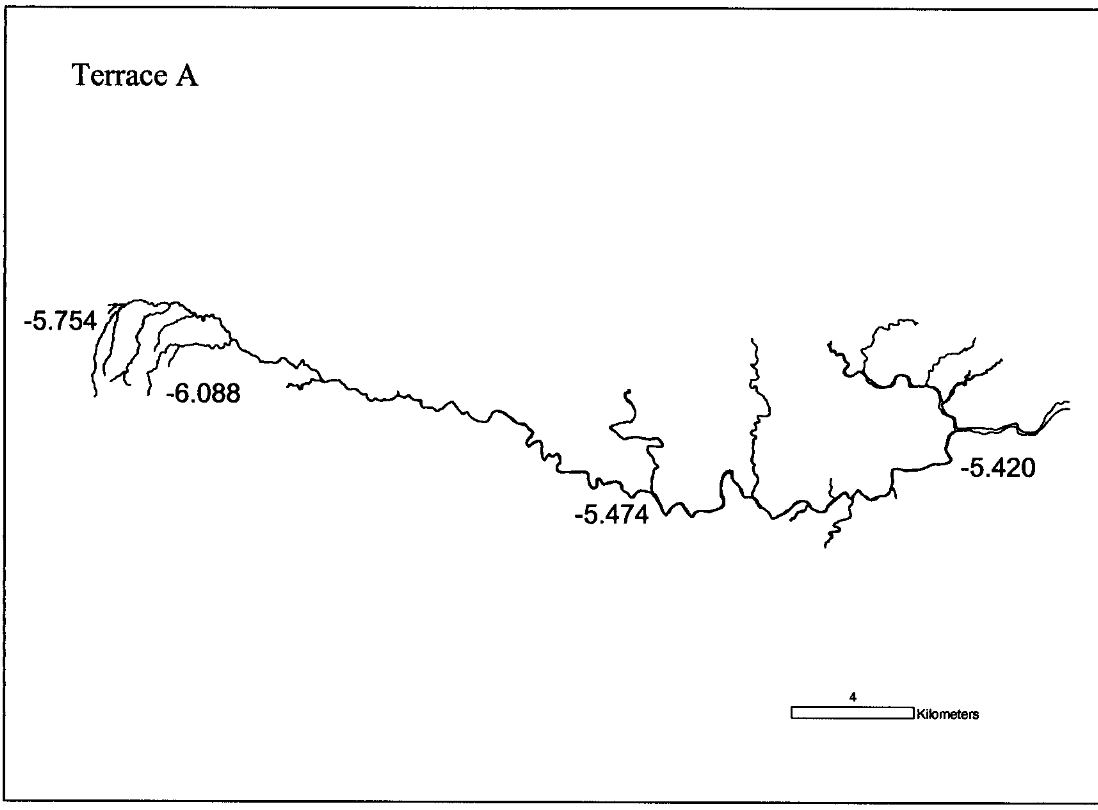


Figure 5.3.1. Graphs to show correlation between TND and B axis measurements.



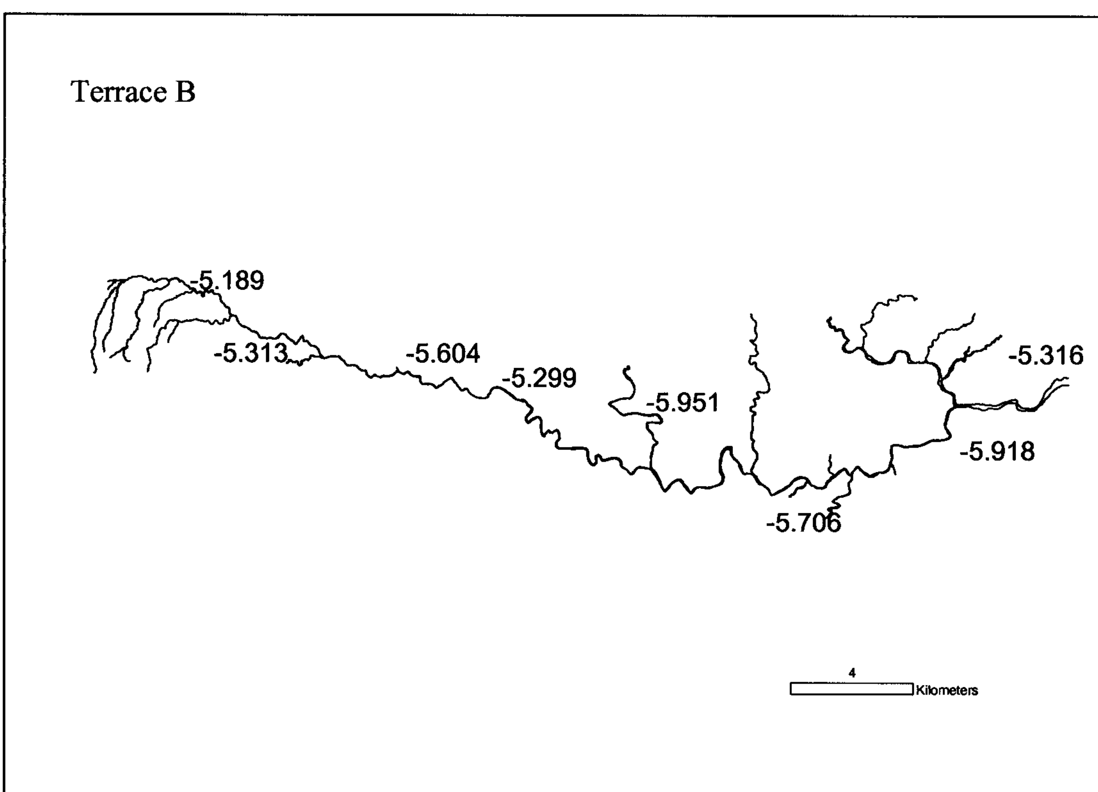
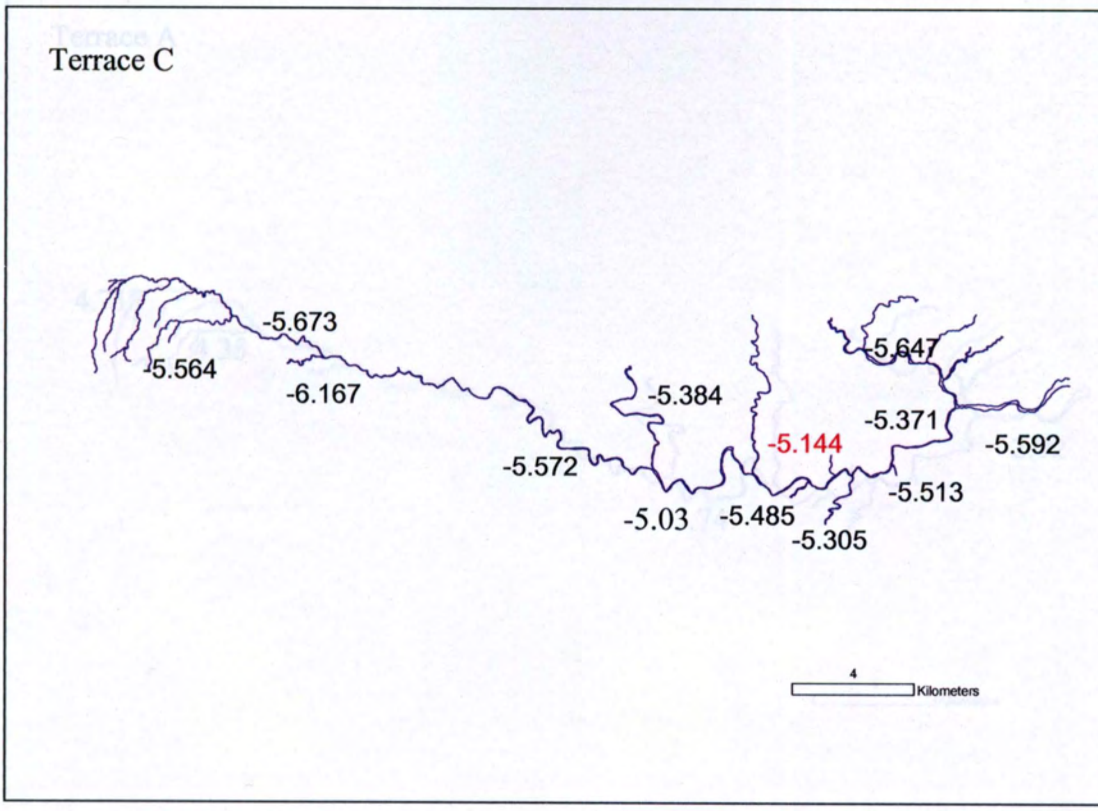


Figure 5.3.2 a. Mean B axis (Phi) for terraces A and B along the Rio Alias.



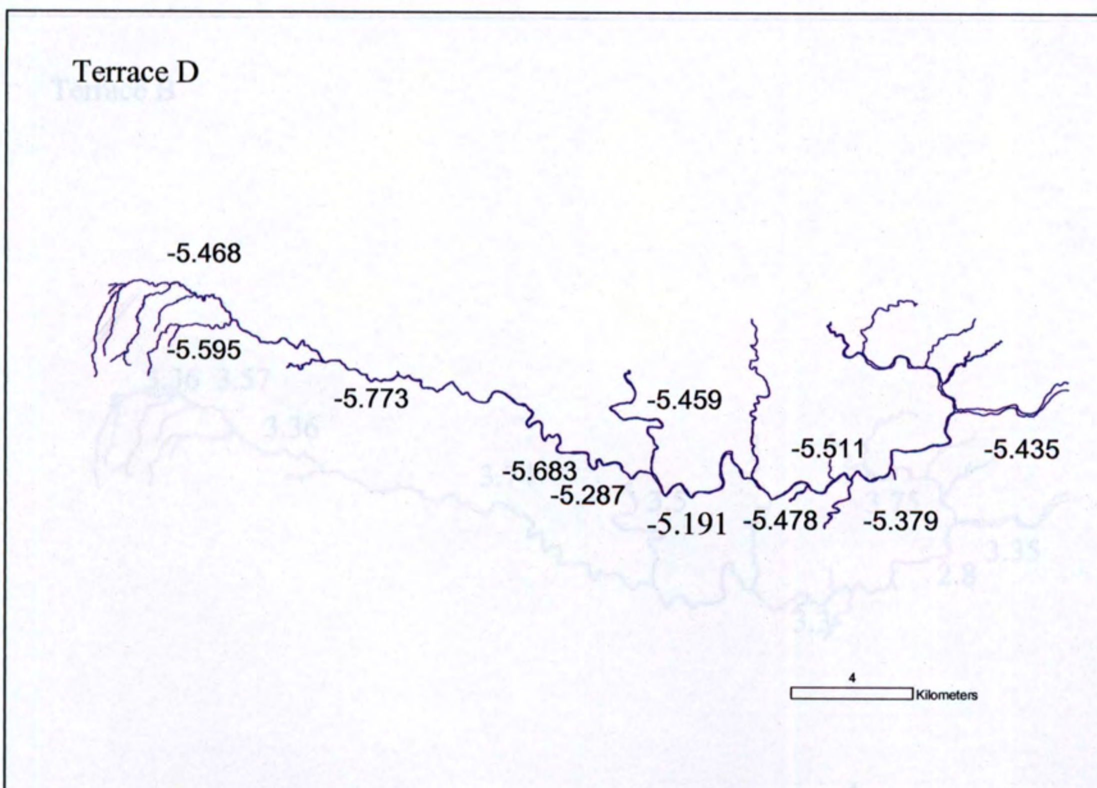
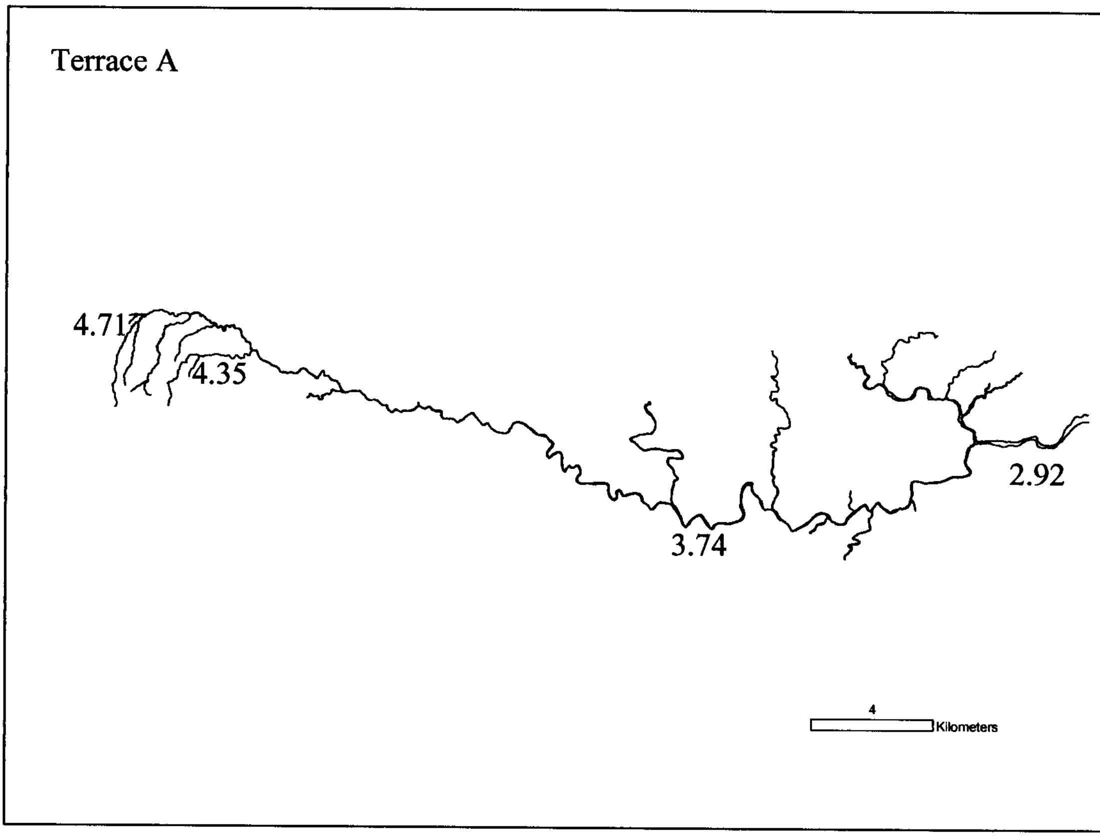


Figure 5.3.2 b. Mean B axis (Phi) for terraces C and D along the Rio Alias.



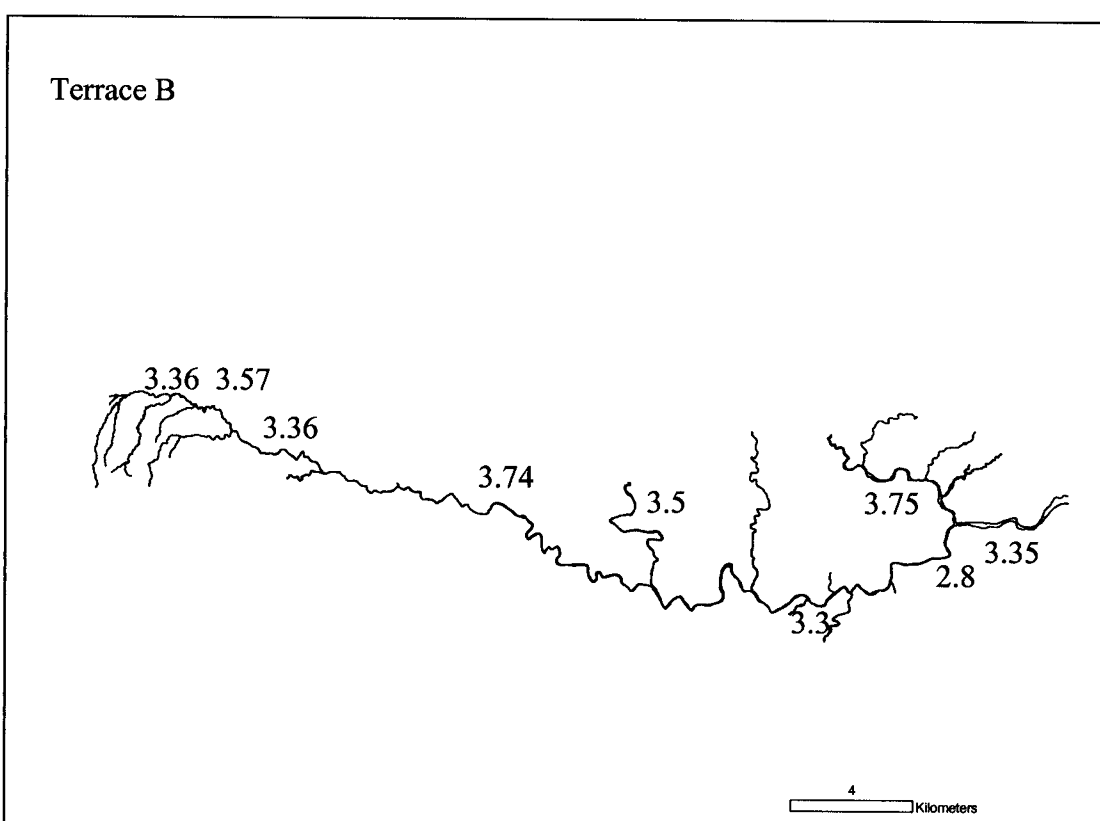
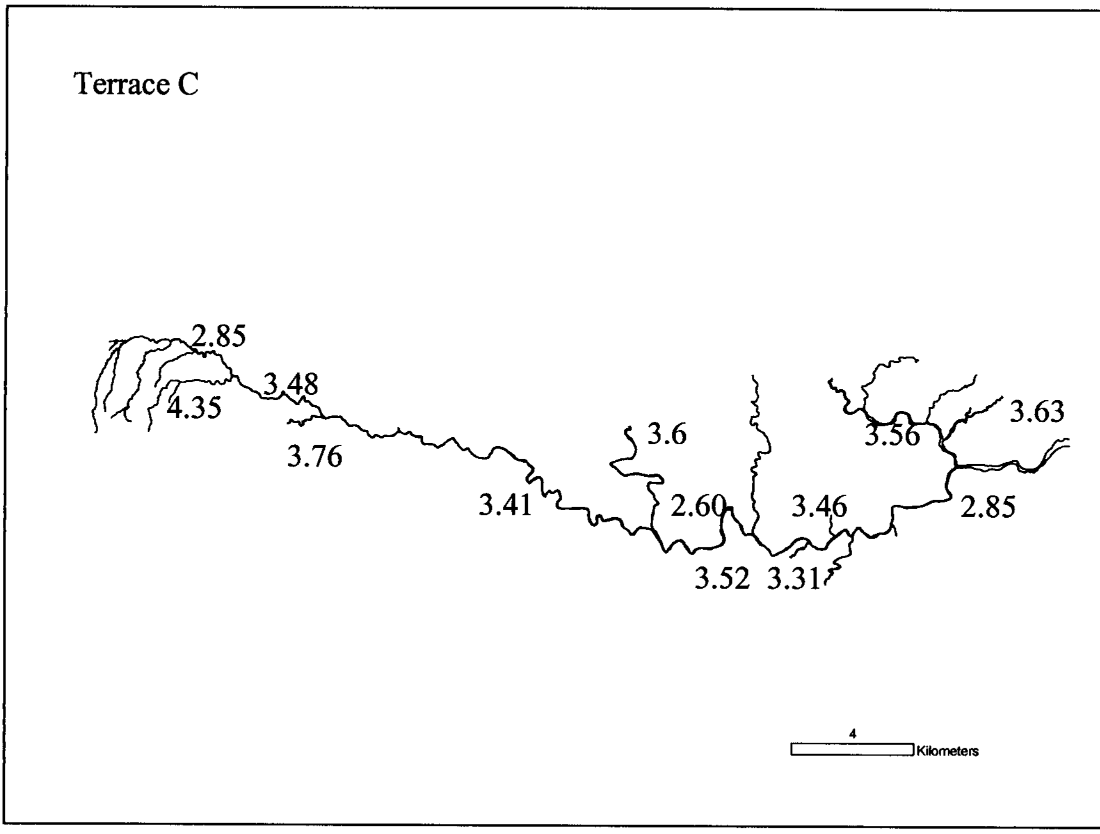


Figure 5.3.3 a. Mean angularity for terrace A and B along the Rio Alias.



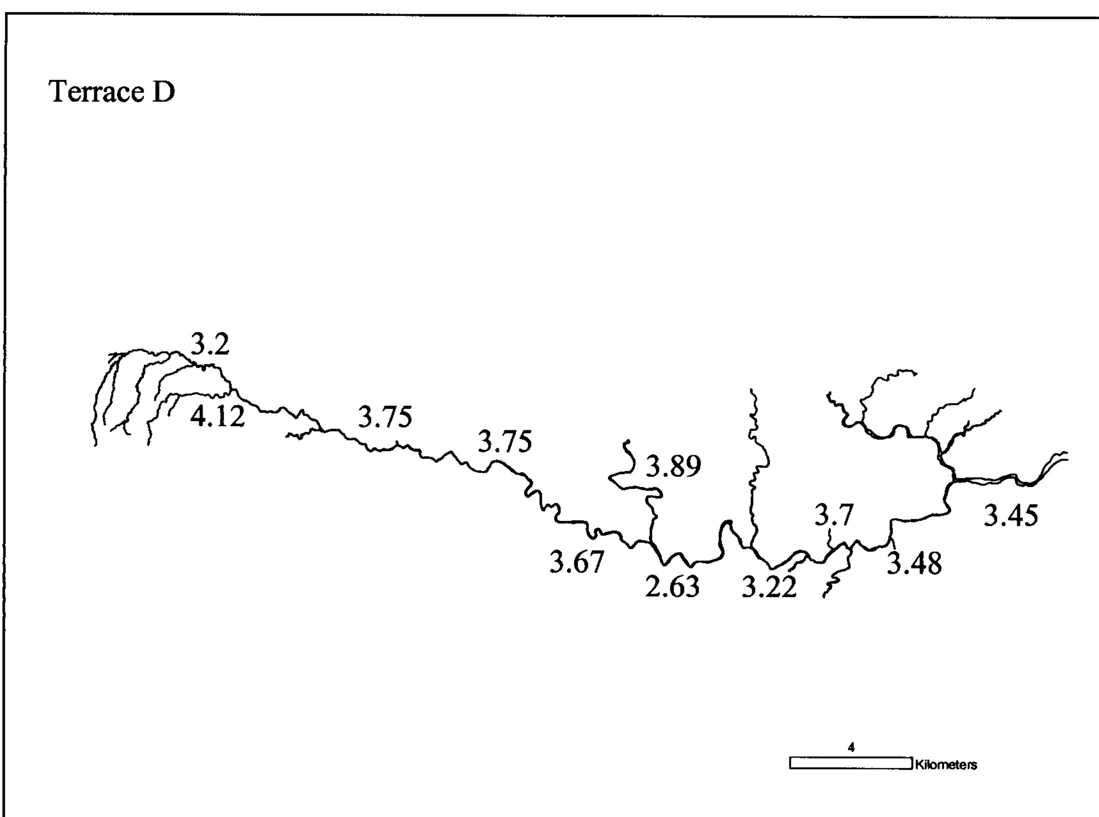


Figure 5.3.3 b. Mean angularity for terrace C and D along the Rio Alias.

headwaters to the coast. Mean roundness values also exhibit an overall increasing roundness downstream, but downstream of a major tributary input, e.g. the Rambla del Saltador, the clasts generally coarsen initially and then recover to exhibit increasing roundness. Terrace C deposits downstream of the Feos junction show a very general downstream decrease in mean B axis and a downstream increase in mean roundness of the clasts. The observations suggest terrace C deposits indicate the same pattern of development downstream as terrace A and B; i.e. downstream of the major tributary inputs (Honda, Feos, Gafares and Saltador) the clasts temporarily coarsen/increase in angularity. Continuing downstream away from the zone of input the clasts return to the overall downstream trend of increasing roundness and to a much lesser extent decreasing grain size.

Terrace D sediments demonstrate no clear downstream pattern in mean B axis clast size but mean roundness values show a clear increase in the degree of roundness from the headwaters to the Feos junction area. But, downstream of the Feos and the Gafares tributary input the clasts increase in roundness once again downstream. There is no obvious difference between the mean clast size of terrace C and D below the Feos confluence as demonstrated by Maher et al. (in press), and this is due to field sampling technique. Particle size data was collected on sediments that were both accessible and representative of the depositional environment of the unit as a whole. For terrace C this meant that particles much smaller than the maximum clast size were measured for A, B and C axis, and for terrace D the average clast size measured was larger than the gravel material characterising the unit. Maximum clast size for terrace C was c.1m on the B axis (Maher et al., in press).

Particle size data shows very little evidence of downstream fining/diminution of the clasts, although in some portions of the system there is a hint of downstream fining. Particle shape data however, suggests a general downstream increase in the degree of roundness of the clasts. Furthermore downstream of the major tributary inputs the clast assemblage temporarily increases in angularity reflecting the local sediment input sourced from the tributary systems. Downstream of the confluence areas the increasing downstream roundness is re-established.

Clast analysis of the terrace sequence indicates throughput of material from the headwaters to the coast on the basis of increasing roundness values, with less localised input than that indicated by the modern channel sediments. Furthermore the evidence presented indicates an overall fining of the clasts from the oldest terraces to the modern channel. This however appears to be somewhat related to the use of B axis measurements on the terraces (as an indication of size) whilst the TND was acquired for the modern channel. The TND values are calculated by taking the cube root of the product of the A, B and C axis and therefore appear to be sensitive to the clasts that have small C axis (indicated on Figure 5.3.1 by the increased spread of values at the finer end of the scale). If the mean B axis was used to represent particle-size patterns on the modern channel (as opposed to the TND) than the clast sizes indicated would be coarser-similar to the terrace sequences (see Appendix 1).

5.3.2.3 Lithological variation of the clast assemblage

Clast analysis of the terrace deposits was carried out using the same lithological units as in the modern channel in section 5.2.2.3.

a) The Lucainena Sub-Reach

Terrace units A-D are represented through the Lucainena sub-reach. Terrace A deposits are preserved in the headwaters of the Lucainena basin on a pediment adjacent to the Rambla del Penoncillo in the vicinity of Lucainena village (Figure 5.3.4). Both remnants are unsurprisingly dominated by clasts sourced from the Alpujarride complex and both have a high proportion of "Other" material, which in this location comprises iron ore. The material appears to be predominantly sourced from the northern flanks of the Sierra Alhamilla rather from the Tortonian rocks of the basin as a whole.

The composition of the terrace B deposits varies through the sub-reach reflecting the variations of source area material. In the headwaters area along the Rambla del Penoncillo (Figure 5.3.4) the assemblage is dominated by Alpujarride material and secondly sandstone and "Other" material, reflecting the local source of iron ore from the Sierra Alhamilla near Lucainena village. Upstream of the confluence with the Rambla Honda the proportion of sandstone has increased and that of the Alpujarride complex decreased, reflecting the increase in the proportion of the source area incised into basin-fill sandstone. In the transverse reach of the sub-reach at Los Olivillos the clast assemblage reflects the increasing proportion of Alpujarride material sourced both from the main channel incising directly into schist and the Rambla Honda tributary supplying 100% Alpujarride material.

Terrace C in the headwaters of the Lucainena village stream is dominated by Alpujarride material (a significant component of which is meta-carbonate) and sandstone (Figure

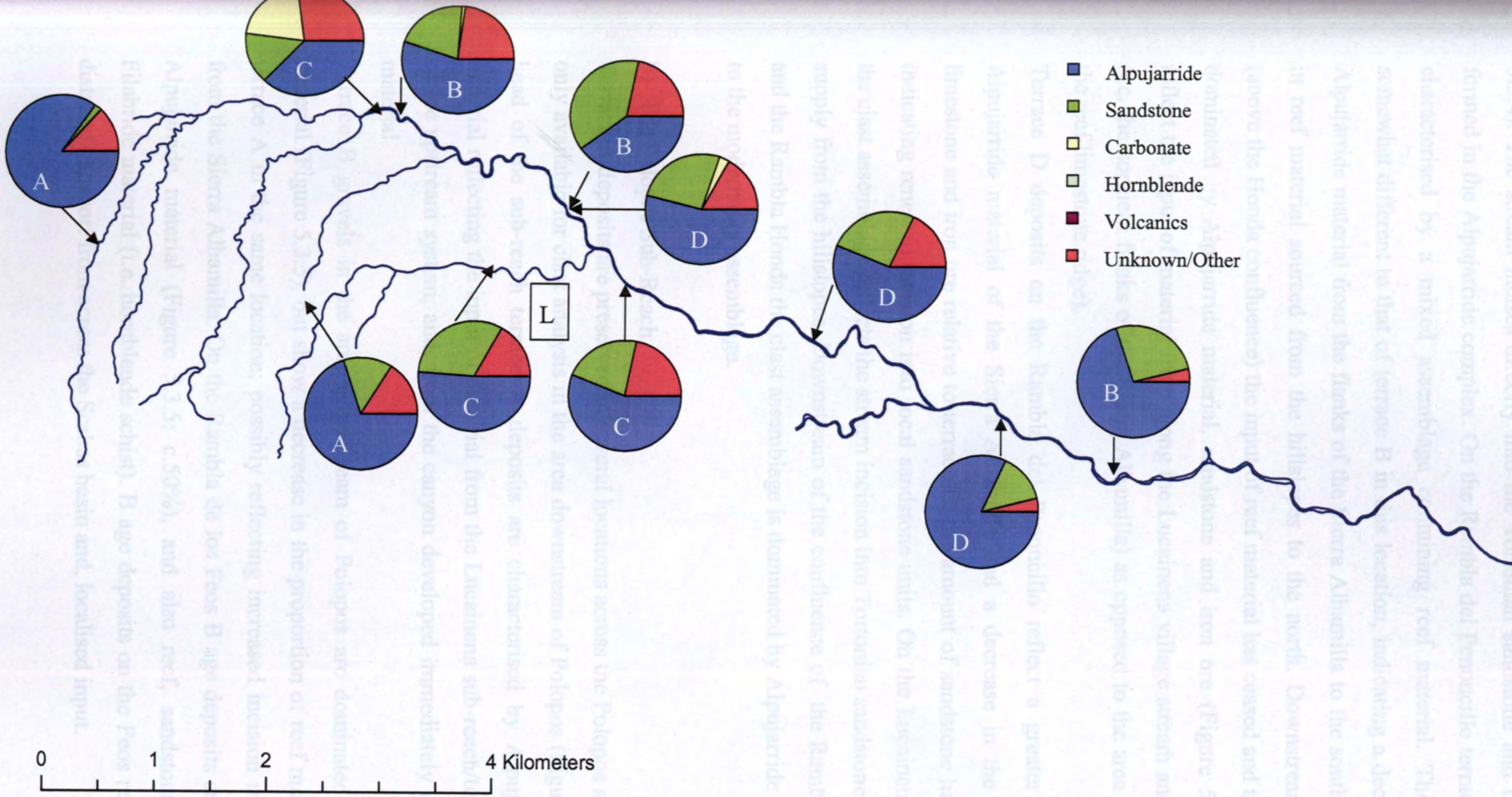


Figure 5.3.4. Clast compositional analysis for the Lucainena sub-reach. Letters indicate terrace stage (A-D). L indicates Lucainena village. N=200.

5.3.4). The stream incises directly into the Tortonian sandstone and the hillslopes are formed in the Alpujarride complex. On the Rambla del Penoncillo terrace C deposits are characterised by a mixed assemblage containing reef material. The assemblage is somewhat different to that of terrace B in this location, indicating a decreased supply of Alpujarride material from the flanks of the Sierra Alhamilla to the south and an increase in reef material sourced from the hillslopes to the north. Downstream at Los Banos (above the Honda confluence) the input of reef material has ceased and the assemblage is dominated by Alpujarride material, sandstone and iron ore (Figure 5.3.4). This may reflect the input of material from along the Lucainena village stream and from the south (i.e. the northern flanks of the Sierra Alhamilla) as opposed to the area to the north (i.e. the reef limestone ridge).

Terrace D deposits on the Rambla del Penoncillo reflect a greater input from the Alpujarride material of the Sierra Alhamilla and a decrease in the amount of reef limestone and iron ore relative to terrace C. the amount of sandstone has also increased indicating renewed incision into local sandstone units. On the Lucainena village stream the clast assemblage reflects the stream incision into Tortonian sandstone and sediment supply from the hillslopes. Downstream of the confluence of the Rambla de Lucainena and the Rambla Honda the clast assemblage is dominated by Alpujarride material, similar to the modern day assemblage.

b) The Polopos Sub-Reach

Terrace A deposits are preserved in several locations across the Polopos sub-reach but are only available for clast analysis in the area downstream of Polopos (Figure 5.3.5). At the head of the sub-reach terrace A deposits are characterised by Alpujarride and reef material reflecting the input of material from the Lucainena sub-reach/transverse portion of the upstream system, and, from the canyon developed immediately upstream in reef material.

Terrace B gravels in the area downstream of Polopos are dominated by Alpujarride material (Figure 5.3.5), but show a decrease in the proportion of reef material relative to terrace A in the same location; possibly reflecting increased incision into and delivery from the Sierra Alhamilla. On the Rambla de los Feos B age deposits are dominated by Alpujarride material (Figure 5.3.5: c.50%), and also reef, sandstone and Nevado-Filabride material (i.e. hornblende schist). B age deposits on the Feos reflect both long-distance transport from across the Sorbas basin and, localised input.

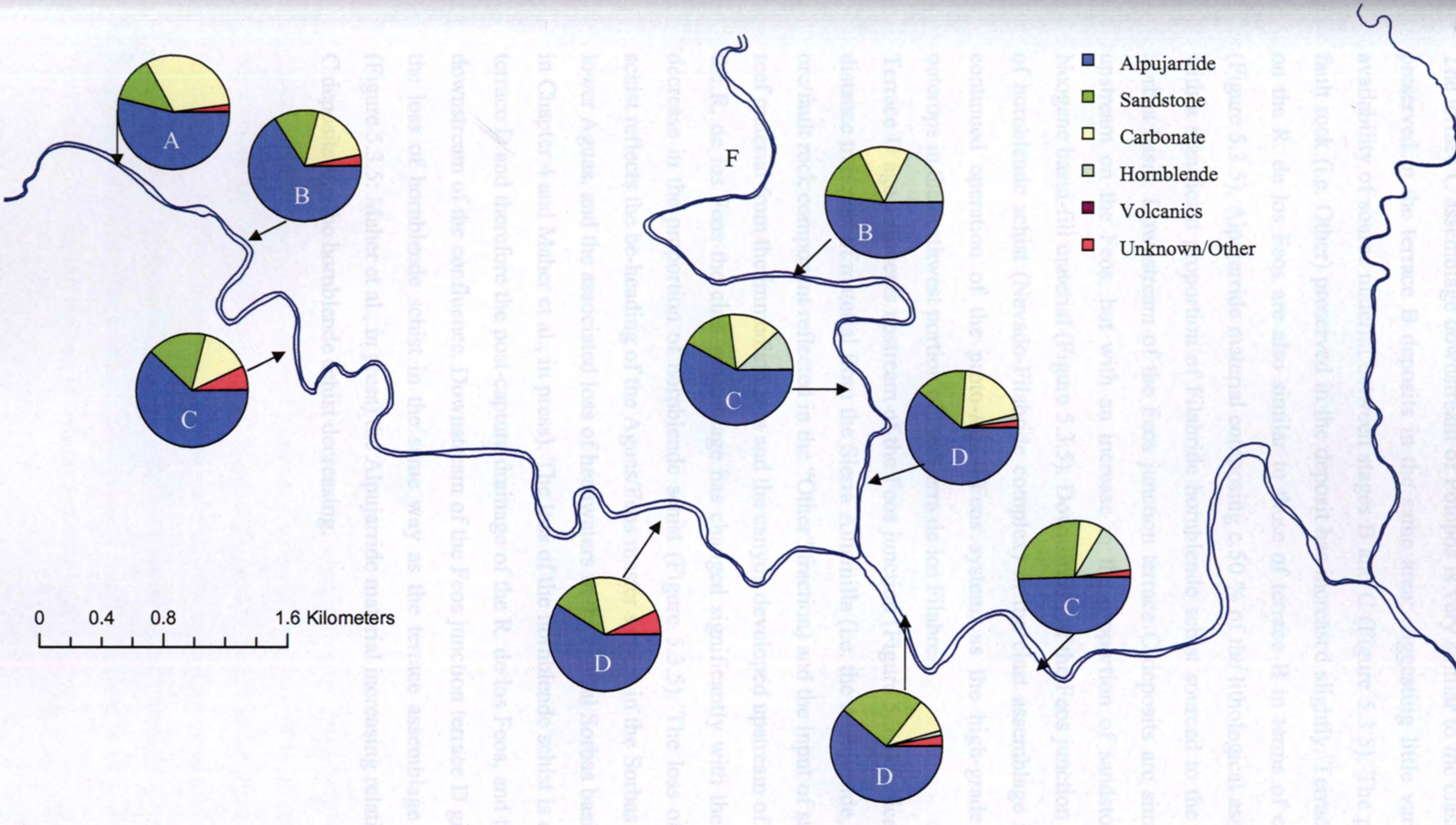


Figure 5.3.5. Clast compositional analysis for the Polopos sub-reach. Letters indicate terrace stage (A-D). F indicates Rambla de los Feos. N=200.

The terrace C assemblage downstream of Polopos is very similar to the clast assemblage preserved in the terrace B deposits in the same area; suggesting little variation in the availability of source material between stages B and C (Figure 5.3.5). The proportion of fault rock (i.e. Other) preserved in the deposit has increased slightly. Terrace C deposits on the R. de los Feos are also similar to those of terrace B in terms of clast analysis (Figure 5.3.5), Alpujarride material composing c.50 % of the lithological assemblage but with a significant proportion of Filabride hornblende schist sourced to the north of the Sorbas basin. Downstream of the Feos junction terrace C deposits are similar to those upstream on the Feos, but with an increase in the proportion of sandstone from the Neogene basin-fill material (Figure 5.3.5). Downstream of the Feos junction the presence of hornblende schist (Nevado-Filabride complex) in the clast assemblage indicates the continued operation of the proto-Aguas/Feos system, as the high-grade schist only outcrops in the northwest portion of the Sierra de los Filabres.

Terrace D age sediments upstream of the Feos junction (Figure 5.3.5) indicate both long distance transport of material from the Sierra Alhamilla (i.e. the Alpujarride, and the iron ore/fault rock component reflected in the "Other" fraction) and the input of sandstone and reef material from the immediate area and the canyon developed upstream of Polopos. On the R. de los Feos the clast assemblage has changed significantly with the pronounced decrease in the proportion of hornblende schist (Figure 5.3.5). The loss of hornblende schist reflects the be-heading of the Aguas/Feos master system in the Sorbas basin by the lower Aguas, and the associated loss of headwaters in the central Sorbas basin (discussed in Chapter 4 and Maher et al., in press). The loss of the hornblende schist is diagnostic of terrace D and therefore the post-capture drainage of the R. de los Feos, and the Rio Alias downstream of the confluence. Downstream of the Feos junction terrace D gravels record the loss of hornblende schist in the same way as the terrace assemblage of the Feos (Figure 5.3.5: Maher et al., in press) the Alpujarride material increasing relative to terrace C deposits and the hornblende schist decreasing.

c) The Argamason Sub-Reach

Preservation of fluvial deposits in the Argamason sub-reach is concentrated in the younger terrace deposits (terraces C and D). No provenance analysis was possible on terrace A, and only one clast count of B age material was possible from the terrace preserved downstream of Argamason village. Terrace B deposits exhibit similar sediment provenance characteristics to those of terrace B of the Rambla de los Feos. The deposits also exhibit an increase in the proportion of basin-fill material particularly sandstone, reflecting the increasing proportion of source area developed in basin-fill material.

Terrace C in the Argamason sub-reach is divided into 2 sub-units: C1 and C2 due to the tectonic complication in this central portion of the system (Maher and Harvey, in press). Terrace C1 is preserved underlying the village of Argamason and the clast content is similar to that preserved within terrace C downstream of the Feos junction in the Polopos sub-reach (Figure 5.3.5 and Fig 5.3.6) though the proportions of the various basin-fill lithologies are slightly different. C2 deposits through the Argamason sub-reach all contain c.4% of hornblende schist (Figure 5.3.6), more than terrace D but less than the terrace C deposits preserved upstream. It is inferred that the proportion of hornblende schist reflects a post-capture phase of evolution, during which stage C1 deposits were re-worked by the channel; incising into alluvium, due to tectonically forced incision (Maher and Harvey, in press). However the proportion of other material varies through the sub-reach. At the head of the sub-reach at the modern nickpoint the clast assemblage is dominated by Alpujarride material, probably reflecting the tributary input from the Arroyo Gafares. Downstream at Argamason the C2 sediments that are deformed by Quaternary activity along the Carboneras Fault Zone exhibit a similar proportion of Alpujarride material to those at the nickpoint (Figure 5.3.6). Downstream of the Argamason deformation the clast assemblage has changed due to the input of volcanic material (brought in along the fault to source the alluvial deposits (Figure5.3.6)). Carbonate material also provides a substantial component of the deposits. Terrace D deposits at the head of the sub-reach are well mixed with almost 50% of the assemblage represented by basin-fill material (Figure5.3.6), and a decrease in the proportion of hornblende schist apparent. Terrace D deposits downstream of the zone of deformation at Argamason are lithologically different to those preserved upstream (Figure 5.3.6). The proportion of Alpujarride material has decreased and the basin-fill and volcanic material constitutes c.60-70% of the coarse sediment assemblage.

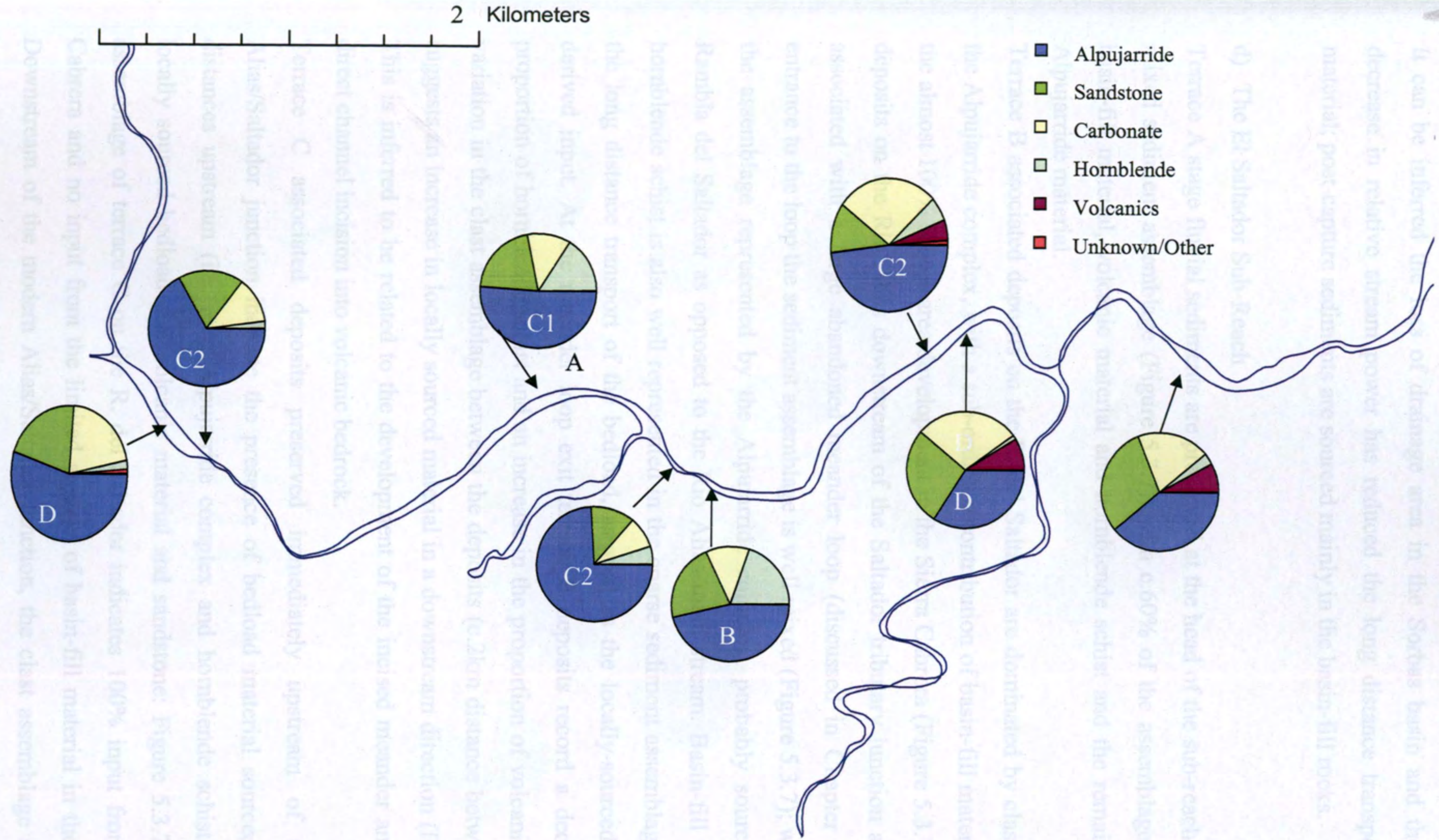


Figure 5.3.6. Clast compositional analysis for the Argamason sub-reach. Letters indicate terrace stage (A-D). A indicates Argamason. N=200.

It can be inferred the loss of drainage area in the Sorbas basin and the consequent decrease in relative stream power has reduced the long distance transport of coarse material; post-capture sediments are sourced mainly in the basin-fill rocks.

d) The El Saltador Sub-Reach

Terrace A stage fluvial sediments are preserved at the head of the sub-reach and reflect a mixed sediment assemblage (Figure 5.3.7), with c.60% of the assemblage made up of basin-fill material, volcanic material and hornblende schist and the remaining 40% of Alpujarride material.

Terrace B associated deposits on the R. del Saltador are dominated by clasts sourced in the Alpujarride complex, with a sub-ordinate contribution of basin-fill material reflecting the almost 100% source area development in the Sierra Cabrera (Figure 5.3.7). Terrace B deposits on the Rio Alias downstream of the Saltador tributary junction are preserved associated with a large abandoned meander loop (discussed in Chapter 4.5). At the entrance to the loop the sediment assemblage is well mixed (Figure 5.3.7); with c.50% of the assemblage represented by the Alpujarride complex, probably sourced from the Rambla del Saltador as opposed to the Rio Alias main stream. Basin-fill material and hornblende schist is also well represented in the coarse sediment assemblage; indicating the long distance transport of the bedload, as well as the locally-sourced Alpujarride derived input. At the meander loop exit terrace B deposits record a decrease in the proportion of hornblende schist and an increase in the proportion of volcanic clasts. The variation in the clast assemblage between the deposits (c.2km distance between the two) suggests an increase in locally sourced material in a downstream direction (Figure 5.3.7). This is inferred to be related to the development of the incised meander and associated direct channel incision into volcanic bedrock.

Terrace C associated deposits preserved immediately upstream of the modern Alias/Saltador junction indicate the presence of bedload material sourced from long distances upstream (i.e. reef, Alpujarride complex and hornblende schist input) and, locally sourced bedload (i.e. volcanic material and sandstone: Figure 5.3.7). The clast assemblage of terrace C on the R. del Saltador indicates 100% input from the Sierra Cabrera and no input from the limited amount of basin-fill material in the catchment. Downstream of the modern Alias/Saltador junction, the clast assemblage suggests the bedload material is dominated by input from the R. del Saltador as the Alpujarride complex dominates the sediment

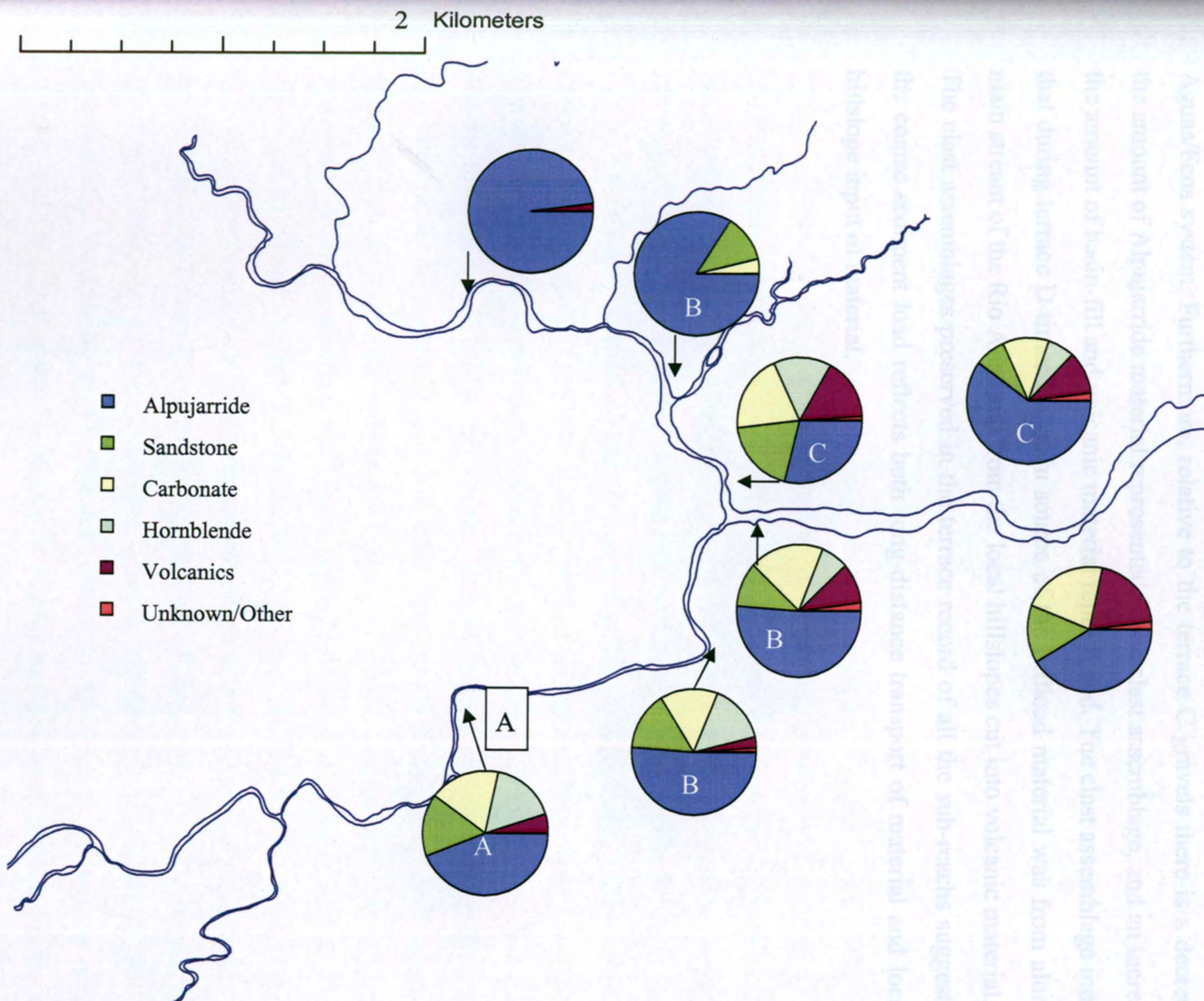


Figure 5.3.7. Clast compositional analysis for the El Saltador sub-reach. Letters indicate terrace stage (A-D). A indicates Llano don Antonio. N=200.

assemblage (Figure 5.3.7). There is however strong evidence of long distance transport of material, indicated by the presence of hornblende schist and reef material.

Terrace D fluvial gravels on the lower portion of the Rio Alias (downstream of the Alias/Saltador tributary junction) exhibit a decrease in the proportion of hornblende schist in comparison with terrace C, related to the upstream beheading of the proto-Aguas/Feos system. Furthermore, relative to the terrace C gravels there is a decrease in the amount of Alpujarride material represented in the clast assemblage, and an increase in the amount of basin-fill and volcanic material represented. The clast assemblage indicates that during terrace D times the main source of the bedload material was from along the main stream of the Rio Alias and from the local hillslopes cut into volcanic material.

The clast assemblages preserved in the terrace record of all the sub-reachs suggests that the coarse sediment load reflects both long-distance transport of material and localised hillslope input of material.

5.3.3 The Suspended Load

5.3.3.1 Introduction

Fine sediment (<2mm) extraction from the terrace sequence was limited by the degree of preservation of sediments, accessibility of sections and the degree of cementation/induration of the deposits. Where terrace deposits were available for fine sediment analysis samples were taken, and similarly to the modern channel, sediments were divided into particle size fractions before undergoing mineral magnetic analysis. Particle size fractions are using the nomenclature presented in section 5.2.3.3. Due to both time and financial restrictions, petrological and SEM analysis could not be performed on the terrace sequence in the current study.

5.3.3.2 Magnetic Analysis

a) The Lucainena Sub-Reach

Across the Lucainena sub-reach, samples for magnetic analysis were collected for terraces C and D only, due to erosion of deposits, cementation of the unit and inaccessibility of the outcrops of older sediments. However, it is the deposits associated with terraces C particularly at the head of the basin that may exhibit variation in provenance due to the postulated capture event at Lucainena village (see Chapter 4).

On the Rambla del Penoncillo terrace C and D deposits are preserved in the portion of the drainage that experienced the loss of headwaters from the area immediately to the south. Terrace C deposits demonstrate the magnetic signal is carried in the coarse sand fraction, and the signal is generated by the concentration of ferrimagnetic minerals (Table 5.3.1). The high values of χ_{LF}, SIRM and Soft IRM indicate the presence of easily magnetized minerals such as magnetite and the low values of HIRM suggest only a small input of canted-antiferromagnetic minerals. This is supported by a Hard % value of 4.5. The high values produced and the fact that the signal is carried in the coarse sand fraction suggests derivation from the zone of iron ore mineralization sourced from c.6km upstream along the Rambla del Penoncillo after the beheading of drainage from Lucainena village. Terrace C deposits on the Lucainena village tributary do not exhibit the same characteristics as those on the Rambla del Penoncillo, all magnetic parameters are lower in value and the signal is dominantly carried in the medium sand fraction (Table 5.3.1). The magnetic analysis indicates the magnetic signal is dominated by the presence of ferrimagnetic minerals with a small proportion of canted-antiferromagnetic minerals present (HIRM is 7% of SIRM). The variation between the two

	χ_{LF} (10^{-8} m^{3}kg^{-1})	SIRM (10^{-5}Am^{2}kg^{-1})	HIRM (10^{-5}Am^{2}kg^{-1})	Soft IRM (10^{-5} Am^2 kg^{-1})
Terrace C R.Del Penoncillo	791.26	14165.69	617.90	5958.49
Terrace C Lucainena village	*116.20*	*2035.87*	*142.10*	*966.00*
Terrace C R. Alias Pre Honda	59.50	1643.64	413.53	356.70
Terrace C R. Honda	32.65	641.24	61.64	317.80
Terrace D R.Del Penoncillo	**129.87** *88.28*	**2391.19** *1483.54*	**183.41** *100.32*	**995.62** *658.50*
Terrace D Lucainena village	133.84 *98.86*	1010.39 *1482.12*	50.52 *67.76*	535.87 *811.42*
Terrace D R. Honda	126.05 48.41	1186.96 723.40	66.68 30.15	554.02 375.36
Terrace D Post Honda	29.51	1335.30 1069.88	113.49 53.01	489.70 449.62

Table 5.3.1. Magnetic properties for terraces in the Lucainena sub-reach (see Figure 5.2.9). Particle size key: Black = silt. Black italic = medium sand. Green = clay. Blue = bulk. Red = fine sand. Purple bold = coarse sand.

streams that are sourced in the same lithological material, is not surprising given the evolutionary differences between the two during terrace C times. The Lucainena village stream was eroding headwards as a newly developed stream due to the base-level fall downstream and consequently would be incising directly into the Tortonian sandstones and marls in the Lucainena valley, generating fine sediment, rather than producing lots of sediment from the more resistant meta-carbonate/schist hillslopes. The Rambla del Penoncillo lost headwaters and could be receiving fine material sourced from upstream

(i.e. Tortonian bedrock and iron ore from the Sierra Alhamilla). The concentration of the magnetic material in the coarse sand further suggests the material has been transported significant distances and winnowed into the fine sediment assemblage from the clast component.
Terrace D deposits in the headwater areas again suggest variation in the magnetic mineral content of the material supplying the Rambla del Penoncillo and the Lucainena village tributary. On the Rambla del Penoncillo the magnetic signal indicates the presence of ferrimagnetic minerals dominantly carried in the coarse sand fraction (Table 5.3.1) with secondary peaks in the fine sand particle-size fraction. The magnetic values are however much lower than those of terrace C, indicating a decrease in the proportion of the ferrimagnetic minerals, or, a dilution effect due to the increased abundance of paramagnetic and diamagnetic material produced by the limestone, sandstone and marl bedrock. It is difficult to indicate any real variation in the paramagnetic/diamagnetic contribution as the magnetic signal is dominated by ferrimagnetic material when it is present. The absolute values are however, similar to those of terrace C on the Lucainena village tributary stream. Terrace D deposits at Lucainena village produce an extremely complex signal (Table 5.3.1). Generally there are two peaks in magnetic values associated with the clay and medium sand particle size fractions. χ_{LF} peaks in the clay fraction whilst SIRM and Soft IRM peak in the medium sand fraction. The absolute value of χ_{LF} is similar between the two samples (i.e. Clay: 133.84 and Medium sand: 98.86 10^{-8} m^3 kg^{-1}). Overall the results suggest the concentration of the magnetic signal associated with ferrimagnetic mineral dominance in the clay and medium sand fractions. HIRM values peak in the medium sand fraction at 67.76 ($10^{-5}Am^2$ kg^{-1}) and indicate the concentration of the canted-antiferromagnetic minerals in this fraction. This is a feasible and likely explanation given the calcareous sandstones that would supply the canted-antiferromagnetic minerals (i.e. haematite/goethite) are incised into by the Lucainena village tributary. Hard % (HIRM as a percentage of the SIRM) indicates similar contributions from the canted-antiferromagnetic minerals (as a proportion of the total remanence signal) for both particle size fractions at 4.5 % (medium sand) and 5% (clay). The clay material is likely to be supplied from the marine marls intercalated with the Tortonian sandstone.

Downstream, above the confluence of the main stream and the Rambla Honda, terrace C deposits exhibit a change in magnetic characteristics from those in the upstream deposits.

The absolute values of the magnetic parameters indicating ferrimagnetic minerals have decreased from the upstream values and the magnetic signal is carried in the silt fraction as opposed to the coarse and medium sand fraction. SIRM and HIRM (Table 5.3.1) indicate the primary signal associated with the remanence carrying minerals is associated with both ferrimagnetic minerals and canted-antiferromagnetic minerals. Terrace C deposits indicate a more substantial contribution from the canted-antiferromagnetic component above the Honda junction with Hard % values of 25%, probably relating to the greatly increased proportion of the source area incising into Neogene basin calcareous rocks.

Analysis of both terrace C and D magnetic properties on the Rambla Honda (Table 5.3.1) indicate the magnetic minerals are concentrated into the clay particle size fraction. χ_{LF}, SIRM and Soft IRM parameters indicate the magnetic mineral assemblage is characterised by ferrimagnetic minerals (i.e. χ_{LF}, SIRM and Soft IRM) with a small proportion of canted-antiferromagnetic minerals, represented by HIRM values and low Hard % of 4-5%. Terrace D deposits on the Rambla Honda exhibit a secondary peak in magnetic values associated with the fine sand particle-size fraction (Table 5.3.1). The signal generated is the same as that in the clay fraction but of a smaller magnitude. The absolute values of the results presented are much higher than the values recorded in the modern channel of the Rambla Honda (Section 5.2.3.3) and indicate an overall decrease in the proportion of magnetic minerals through time. The results then suggest a variation in the mineralogical content of the Alpujarride material the Rambla Honda has been incising into with time.

Downstream of the Rambla Honda terrace D deposits exhibit overall similar absolute values to those of terrace D on the Rambla Honda (Table 5.3.1), there are however subtle variations between the two. Magnetic properties (excluding χ_{LF} due to sample size) peak in the silt particle-size fraction and suggest an increase in the proportion of canted-antiferromagnetic minerals as indicated by HIRM, and a decrease in the proportion of ferrimagnetic minerals, as indicated by Soft IRM, downstream of the Honda confluence. This indicates that the input of material from along the main stream is concentrated into the silt fraction, similar to the modern system.

In the Lucainena sub-reach the presence of the ferrimagnetic minerals associated with the Sierra Alhamilla is likely to dominate the magnetic signal generated and mask any signal generated by the less magnetic marls and sandstones sourced from the Neogene basin-fill. However clear patterns are discernable and can be related to the geomorphological evolution of the system. This will be discussed in the next section. χ_{LF} was not measured on some samples due to the limited sample size, however in the samples where the magnetic signals were carried in the coarser fractions recovery was good and the absence of χ_{LF} in the silt and clay fraction is clear.

b) The Polopos Sub-Reach

In the Polopos sub-reach two samples associated with the pre-capture drainage terrace sequence where sampled above and below the Alias/Feos confluence. Terrace B is preserved and was sampled for fine sediment provenance analysis above the Alias/Feos junction (Table 5.3.2). The magnetic signal is carried in the fine and medium sands and in the clay particle-size fractions. The highest values are recorded in the medium sand

	χ_{LF} (10^{-8} m^3 kg^{-1})	SIRM (10^{-5}Am^2 kg^{-1})	HIRM (10^{-5}Am^2 kg^{-1})	Soft IRM (10^{-5} Am^2 kg^{-1})
Terrace B	*89.12*	*1251.38*	*52.11*	*724.51*
R.Alias Pre-Feos	77.97	1060.34	63.73	581.74
		1073.19	52.21	554.98
Terrace C	363.76	3012.32	415.38	959.93
R.Alias Post-Feos				
Terrace D	*71.68*	*1237.37*	*46.28*	*571.92*
R.Alias Pre-Feos		921.65	68.01	479.85
		903.74	54.55	455.06
Terrace D Feos	124.27	2020.71	145.71	958.13
Terrace D	17.02	469.70	57.22	175.25
Post-Feos	17.19	464.00	83.98	132.38
		523.90	*81.79*	*207.65*

Table 5.3.2. Magnetic properties for terraces in the Polopos sub-reach (see Figure 5.2.9). Particle size key: as Table 5.3.1.

fraction with similar values recorded in the fine sand and clay fractions. The magnetic signal is dominated by that associated with the presence of ferrimagnetic minerals (i.e by the χ_{LF}, Soft IRM and SIRM) with a small proportion of canted-antiferromagnetic present indicated by the HIRM values and a Hard % of between 5 and 6%. The absolute values recorded are greater than those recorded on the modern channel for the Rio Alias upstream of the Feos confluence (Section 5.2.3.3) though the overall magnetic signal is similar in terms of the mineral assemblage. It is inferred this is related to variations in travel time of the fine sediment load between the modern channel and the older terrace sequence; earlier in the evolution of the fluvial system transportation of fine sediment may have been over longer distances (i.e. sourced from the Lucainena sub-reach) than the modern systems achieves (to be discussed below).

Terrace C deposits are preserved below the Alias/Feos junction and therefore relate to the throughput of the Aguas/Feos master system. The magnetic signal is carried in the fine sand (Table 5.3.2) fraction and indicates the presence of ferrimagnetic minerals and canted-antiferromagnetic minerals, though the signal would appear to be dominated by the ferrimagnetic assemblage (i.e. χ_{LF}, SIRM and Soft IRM: Table 5.3.2). The values recorded are relatively higher than those in the same location on the modern channel indicating a possible variation in source area mineralogical characteristics.

Terrace D (post-capture drainage) deposits are preserved on the main Rio Alias, the Rambla de los Feos and the Rio Alias below the Feos confluence (Table 5.3.2). On the Rio Alias above the Feos, terrace D deposits exhibit the same characteristics as the terrace B deposits peaking overall in the medium sand fraction (Table 5.3.2). There are two further peaks in the magnetic signal in the fine sand and clay fractions though they are slightly less than the absolute values in the medium sand. The magnetic signal indicates the presence of ferrimagnetic signals and canted-antiferromagnetic minerals and the relatively high values of χ_{LF} SIRM and Soft IRM compared with the HIRM values suggest the signal is dominated by the ferrimagnetic component. Low Hard % values of 4-7% also indicate there is only a small proportion of canted-antiferromagnetic minerals. The analysis also indicates the peak concentration of HIRM (and Hard % at 7%) in the fine sand fraction; probably relating to calcareous sandstone liberation from the local Cuevas Viejas sandstone and the input of haematite and goethite. On the Rambla de los Feos terrace D deposits exhibit the partitioning of the magnetic signal into the fine sand particle-size fraction (Table 5.3.2).The absolute values are higher than those recorded on the Rio Alias above the confluence and suggest the mineral assemblage contains a greater proportion of magnetic minerals. The χ_{LF}, SIRM, HIRM and Soft IRM values indicate the presence of ferrimagnetic and canted-antiferromagnetic minerals, the ferrimagnetic assemblage dominating the magnetic signal. The HIRM values are higher on the Feos than on the Rio Alias possibly indicating a greater proportion of canted-antiferromagnetic minerals along the Feos, possibly related to incision into calcareous sandstone and the liberation of haematite and goethite. The Hard % value is 7% on the Rambla de los Feos, more than that of the Rio Alias overall, though both Hard % values peak on both streams in the medium sand fraction. Downstream of the confluence the magnetic assemblage is complicated in terrace D. The magnetic signal (excluding χ_{LF}) is carried in the fine sand, silt and clay fraction (Table 5.3.2) and the values are lower than for terrace D upstream of the confluence on both feeder systems. The magnetic analysis indicates an overall decrease in the presence of ferrimagnetic material, though χ_{LF} was not measured for the samples in this particle size range as the values where inaccurate due to very low sample sizes. The remanence characteristics suggest the signal is strongest in the clay fraction and reflect the presence of ferrimagnetic material with little canted-antiferromagnetic material present. The terrace D magnetic analysis indicates a downstream decrease in the proportion of magnetic minerals present. This may be due to the post-capture evolution of the downstream portion of the Rio Alias. Once the headwaters had been lost and the input of magnetic high-grade metamorphic material shut-off (indicated by the presence of a strong magnetic signal in terrace C) the main source of sediment was from the upstream portion of the Alias system and from local incision into Neogene bedrock material. In this reach of the Rio Alias the river system is incising into calcareous sandstones, marl and gypsum. This increase in paramagnetic and diamagnetic material accompanied by a loss in ferrimagnetic material from the Rambla de los Feos, would decrease the overall magnetic signal. The variation between terrace C and D deposits downstream of the Alias/Feos junction and the decrease in the magnetic signal points towards the beheading of drainage as the main cause of contrast in the magnetic properties of the two deposits. Terrace D deposits on the Feos would have been supplied dominantly by Alpujarride schist and thus would have a greater magnetic signal than the downstream portion of the system supplied by sandstone and marl. Terrace D deposits downstream of the Feos junction indicate localised sediment sources.

The magnetic signal generated throughout the terrace sequence can be explained by source area provenance variation, and by changes in the transportational processes through time (i.e. early evolution of the system indicates the long-distance transport of material from upstream whereas the modern channel indicates localised input) and the consequent variation in the location of the source of the sediment supply.

c) The Argamason Sub-Reach

In the Argamason sub-reach there are limited terrace deposits available for fine sediment analysis due to the cemented nature of the deposits particularly those associated with terrace stage C2. Consequently the stage C2 and D deposits analysed are located downstream of the fault zone at and below the Palmerosa tributary. C1 deposits are preserved underlying the village of Argamason and have not been heavily cemented so analysis was possible.

Terrace stage C1 was associated with the pre-capture Aguas/Feos master drainage and the presence of hornblende schist in the clast content is indicative of this through drainage.

	χ_{LF} (10^{-8} m^3 kg^{-1})	SIRM (10^{-5}Am^{2}kg^{-1})	HIRM (10^{-5}Am^{2}kg^{-1})	Soft IRM (10^{-5}Am^{2}kg^{-1})
Terrace C1	54.68	569.01	43.41	249.06
Argamason	73.66	531.17	22.91	271.44
Terrace C2	254.40	1465.12	142.04	746.00
Below the	*81.24*	*875.86*	*86.41*	*420.16*
Palmerosa		650.14	67.57	283.07
Terrace D	92.67	879.66	66.50	432.59
Palmerosa	*50.15*	*661.73*	*71.31*	*302.53*
		996.90	56.20	425.12
		858.44	59.37	387.78

Table 5.3.3. Magnetic properties for terraces in the Argamason sub-reach (see Figure 5.2.9). Particle size key as Table 5.3.1.

The magnetic analysis presented in Table 5.3.3 suggests the presence of ferrimagnetic minerals in the sample indicated by the χ_{LF}, SIRM and Soft IRM parameters. There is proportionally only a small amount of canted-antiferromagnetic material indicated by the HIRM values (Table 5.3.3). This is also reflected in the Hard % (HIRM as a proportion of the SIRM) values of 7% (silt) and 4% (clay) of terrace C1. The magnetic signal as elsewhere in the basin is concentrated into particular particle-size fractions, in terrace C1 the clay and silt fractions exhibit the peak magnetic values. The ferrimagnetic signal is dominating the magnetic signature of the sediments. However the absolute values presented are substantially decreased from those associated with terrace C below the Feos junction c.6km upstream. This suggests that the mineral assemblage has changed between the two locations. Two explanations can be put forward for this occurrence; (i) the amount of fine grade material transported from the Sorbas basin has decreased downstream, therefore exhibiting a downstream decrease in supply, or, (ii) the input of newly eroded calcareous (paramagnetic) minerals has diluted the signal at Argamason and there has been no decrease in fine sediment supply from the Aguas/Feos system. Of these, the latter seems to be the most likely.

Terrace C2 deposits preserved downstream of the Palmerosa tributary are located adjacent to an outcrop of volcanic bedrock that has been brought in along the Carboneras Fault Zone. The volcanic rocks introduce a new source area lithology into the system. The terrace C2 deposits are also post-capture and reflect the shutting off of sediment supply from the Sorbas basin, and a phase of tectonic deformation in the Argamason sub-reach. The high magnetic values relate to the input of local volcanic rock. The magnetic analysis again highlights the partitioning of the magnetic mineral peaks into discreet particle-size ranges (Table 5.3.3). In the Argamason sub-reach the signal is carried in the fine and medium sands and the clay fraction. Magnetic parameters peak in the fine sand fraction. χ_{LF}, SIRM and Soft IRM concentration parmameters all peak in the fine sand fraction and indicate the assemblage is dominated by the presence of ferrimagnetic minerals. The values presented for medium sand and clay are similar in value (excluding χ_{LF} as the sample was too small to be measured accurately) and again suggest the assemblage is dominated by ferrimagnetic minerals. All particle-size fractions have small, but higher than for other sites, values of HIRM, suggesting there is a small canted-antiferromagnetic component. This is reflected in the Hard % values of 10% for each particle-size. However, the dominant signal is carried in the fine sand fraction, and it again may be suggested that this relates to the local input of volcanic material. The volcanic rocks weather quickly into sand sized particles due to the weakly resistant nature of the rock and the size of the particles forming the rock matrix. Upon liberation the material quickly enters the fine sediment assemblage, therefore the indicating a local source of sediment supply. The values presented are a little higher than those indicated on the modern channel downstream of the Palmerosa tributary (Table 5.2.10). This may be related to an increasing proportion of calcareous sandstone getting in to the modern system as the channel then incises directly into the Cuevas Viejas sandstone. However, where the magnetic signal is dominated by the ferrimagnetic component the paramagnetic signal is effectively swamped, causing the interpretation to recognise only the ferrimagnetic component. Samples taken from the main channel when studied on the SEM and in thin section, indicate the paramagnetic (carbonate) minerals are present in abundance. Therefore we must be careful when interpreting the magnetic results alone as they will be biased by the strongly magnetic signature which may not reflect the general mineral assemblage present in the sample.

Terrace D deposits adjacent to the Palmerosa tributary, display a complex magnetic signal (Table 5.3.3) with 4 particle-size fractions showing similar peaks in magnetic value. Fine and medium sand and the silt/clay fractions all carry strong magnetic signals (Table 5.3.3). χ_{LF} was not measured on the silt and clay fraction due to the small amount of sample recovered, however all parameters (χ_{LF}, SIRM, HIRM and Soft IRM) indicate the dominance of ferrimagnetic minerals in the sample. HIRM peaks in the medium sand fraction where χ_{LF}, SIRM and Soft IRM values are at there lowest indicating the increased presence of canted-antiferromagnetic minerals in the medium sand fraction. Hard % also peaks in the medium sand fraction at 10.5% relative to 7% in the fine sand and clay, and 5% in the silt. This again is likely to reflect the local sediment supply of material from the calcareous Cuevas Viejas sandstone and the input minerals such as haematite and goethite. The sandstone is composed of fine to coarse sands and due to its varying lithofacies, in this area the material is relatively uncemented and easily eroded and supplied to the fine sediment load. The absolute magnetic values are lower on the modern channel again in this portion of the system (see Table 5.2.10) indicating during terrace C2 and D evolution there may have been a source of material with a stronger ferrimagnetic component, or over time the amount of calcareous material supplied to the system has increased thus diluting the magnetic signal. It is difficult to ascertain which mode is responsible for the variation of the magnetic signal through time, though during stage C2 and D the river was incising through its own alluvium and re-working sediment that had a significant proportion of Aguas/Feos material present, in the coarse load at least.

The basic magnetic analysis of the terrace sediments preserved in the Argamason sub-reach highlights the particle-size partitioning of the magnetic grains and also suggests the importance of local sediment input to the fine sediment load. Particle-size partitioning can be understood when related to the nature of the bedrock material (and therefore the source material) in terms of the calibre of the material supplied to the system.

d) The El Saltador Sub-Reach

Terrace deposits are preserved for terraces A-D in the El Saltador sub-reach though remnant patches are scarce. Terraces A, B and C on the Rio Alias upstream of the Rambla del Saltador confluence have been sampled as have terraces C and D on the Rambla del Saltador itself. Sediment preservation downstream of the confluence is very poor and the deposits that do remain are heavily cemented and indurated and could not be sampled for fine sediment analysis. Analysis of terrace A deposits at the village of Llano Don Antonio at the head of the sub-reach, again indicate the partitioning of the magnetic signal into separate particle size-fractions (Table 5.3.4). The dominant signal is carried in the fine sand particle-size fraction and χ_{LF}, SIRM and Soft IRM parameters indicate the presence of ferrimagnetic minerals.

	χ_{LF} (10^{-8} m^3 kg^{-1})	SIRM (10^{-5} Am^2 kg^{-1})	HIRM (10^{-5} Am^2 kg^{-1})	Soft IRM (10^{-5} Am^2 kg^{-1})
Terrace A Llano	62.89	640.48	112.50	230.54
Don Antonio		*414.39*	*54.74*	*159.46*
		349.39	49.90	140.58
		438.07	66.44	183.92
Terrace B loop	198.16	1383.79	64.16	756.58
entrance	*177.97*	*1151.30*	*61.10*	*628.30*
		892.23	94.24	445.20
		810.23	42.13	380.34
Terrace C	22.07	134.43	42.27	33.12
nickpoint		123.51	24.39	35.81
		87.39	20.18	19.28
Terrace C R. Del		708.86	109.70	285.50
Saltador		*737.75*	*139.99*	*225.79*
	51.02	488.28	68.71	210.82
Terrace D R. Del	41.67	754.49	125.74	205.08
Saltador	*32.41*	*659.26*	*118.99*	*162.15*
		1512.25	308.79	225.70

Table 5.3.4. Magnetic properties for terraces in the El Saltador sub-reach (see Figure 5.2.9). Particle size key: as table 5.3.1.

However the HIRM values also peak in the fine sands and exhibit a much closer value to the Soft than anywhere else in the drainage basin. This suggests the canted-antiferromagnetic component is of greater importance to the overall magnetic signal generated here than anywhere else in the basin, though the absolute values are not as high as those recorded in other terrace deposits (e.g. terrace C on the Rambla del Penoncillo). This is reflected in the proportion of SIRM represented by the HIRM, i.e. Hard % is 17.5% for the fine sand fraction, and between 13-15% for the other particle-sizes. The partitioning of the signal into the fine sand fraction probably relates to the source of the sediments transported from upstream (i.e. the Cuevas Viejas sandstone and the volcanic rocks). The village of Llano Don Antonio is surrounded by volcanic material and if the sediment supply was local then there would be a stronger magnetic signal. The magnetic analysis indicates that the dominant sediment supply is from upstream deposits of sandstone and to a lesser extent the volcanic rocks. The peak in the fine sand and the associated proportion of canted-antiferromagnetic minerals indicate derivation from the marine calcareous sandstone upstream. There is however a dominance of ferrimagnetic minerals and it is inferred that this is related to local input of the easily eroded volcanic rock. Furthermore the decrease in the absolute value of the magnetic parameters in the silt and clay fractions, also points to a weaker magnetic source area supplying the fine grained material, and not to the local strongly magnetic volcanic rock.

Terrace B sediments preserved at the entrance to the large abandoned meander loop were sampled for magnetic analysis (Table 5.3.4). Results indicate the concentration of the magnetic minerals into several particle size fractions. The magnetic signal again peaks in the fine sand fraction with a close secondary peak in the medium sand fraction (Table 5.3.4). The patterns exhibited by the magnetic parameters demonstrate the same overall pattern as those in terrace A, though the individual values are higher. χ_{LF}, SIRM and Soft IRM parameters indicate the presence and dominance of the ferrimagnetic component in the sediment assemblage in both the fine and medium sands. The silt fraction (though χ_{LF} was not measured due to the small sample size) indicates the dominance of ferrimagnetic grains, as Soft IRM values are significantly higher than HIRM values. However the SIRM and Soft IRM values decrease in the silt fraction and the HIRM values peak indicating that the presence of canted-antiferromagnetic minerals has increased relative to the other particle-size fractions. Hard % values are lower than those of terrace A (ranging from 4-10.5%), though similar to HIRM they peak in the silt fraction at 10.5% indicating the peak concentration of the canted-antiferromagnetic minerals in the silt fraction.

Upstream, at the head of the sub-reach the canted-antiferromagnetic minerals peaked in the fine sand fraction, indicating a downstream winnowing of the particles sourced from the Cuevas Viejas sandstone upstream. A basic interpretation of the results would suggest that the increase in the ferrimagnetic material is due to the input of volcanic material the channel has been incising directly into for c.3km and this is concentrated into the fine sand fraction due to the weathering characteristics of the volcanic rocks.

Terrace C is preserved at the head of the El Saltador sub-reach by the modern day nickpoint, upstream of Llano don Antonio, and on the Rambla del Saltador (Table 5.3.4). The magnetics values recorded for terrace C at the head of the sub-reach are some of the lowest recorded in the drainage basin as a whole and indicate that the canted-antiferromagetnic component is more significant than the ferrimagnetic component (i.e. HIRM values are greater than Soft IRM values). Hard % values range between 23 % in the clay fraction, 20 % in the silt fraction and 31.4 % in the fine sand fraction, further indicating the dominance of canted-antiferromagnetic minerals in the sediment assemblage. The overall remanence values are low, and the χ_{LF} measured on the fine sand fraction is low indicating the presence of canted-antiferromagnetic minerals, and possibly the presence of paramagnetic minerals diluting the magnetic signal. HIRM peaks in the fine sand fraction and again it is inferred that this may relate to the source of the canted-antiferromagnetic minerals in the Cuevas Viejas sandstone. Furthermore the channel upstream is developed into a canyon incising into the sandstone unit that in places comprises quartz pebble conglomerates, this material would supply a diamagnetic mineral assemblage diluting the magnetic signal.

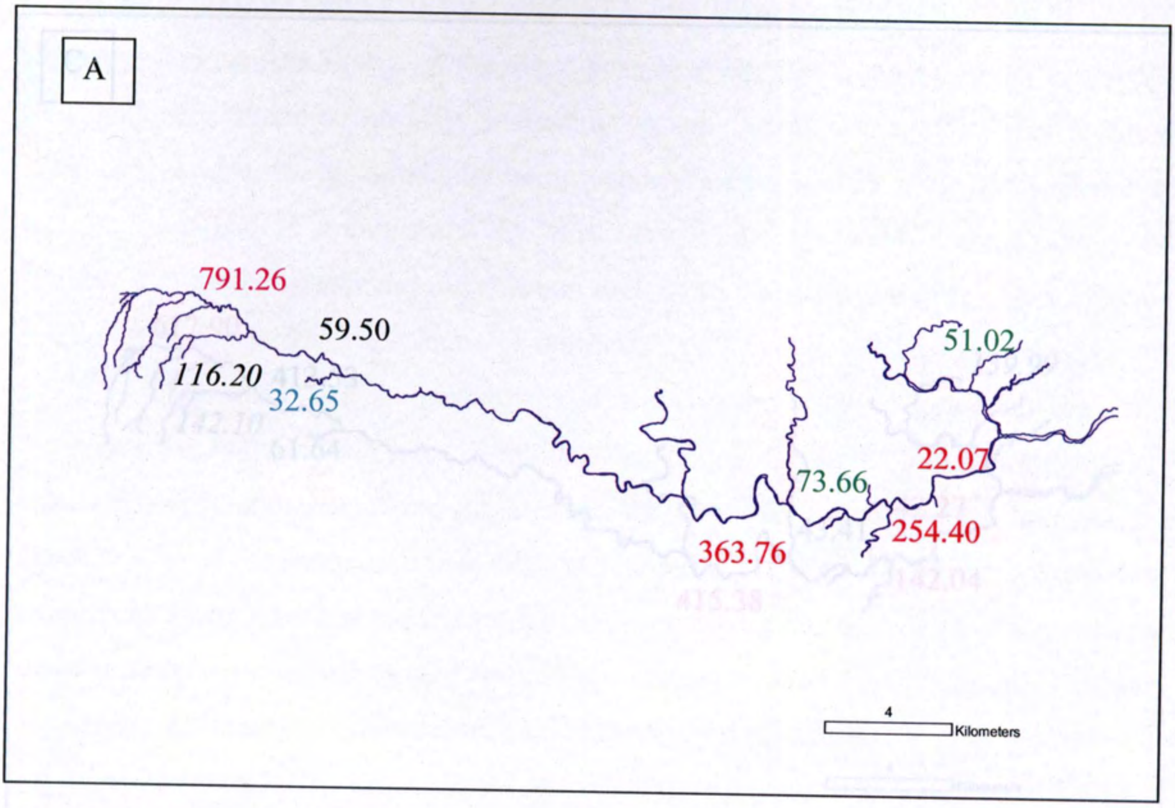
Terrace C on the Rambla del Saltador exhibits a stronger magnetic signal than that on the Rio Alias upstream of the confluence. Overall the sediment is of a fine nature with little sand-sized material recovered from the unit rendering χ_{LF} values immeasurable. Remanence measurements peak in the medium sand fraction and indicate the presence of ferrimagnetic minerals (i.e SIRM and Soft IRM values) and canted-antiferromagnetic minerals (HIRM). The ferrimagnetic assemblage dominates the magnetic signal in a way similar to the characteristics displayed on the Rambla Honda in the Lucainena sub-reach: another tributary sourced almost wholly in the Alpujarride complex. The absolute values of χ_{LF}, SIRM and Soft IRM are higher on the Rambla del Saltador than on the Rambla Honda and this may relate to the presence of some high-grade metamorphic material in the Sierra Cabrera.

Terrace D deposits on the Rambla del Saltador exhibit magnetic characteristics somewhat different from those associated with terrace C (Table 5.3.4). The fine and medium sand fraction display similar absolute values and the same pattern of variation between the parameters (i.e Soft IRM values are greater than HIRM values). However there is an increase in the values of the remanence parameters in the silt fraction (Table 5.3.4). In the sands ferrimagnetic minerals dominate the magnetic signal though canted-antiferromagnetic minerals are indicated by the HIRM parameter. Hard % values of 16.5% (fine sand) and 18 % (medium sand) indicate a significant proportion of canted-antiferromagnetic minerals. χ_{LF} could not be measured on the silt fraction (due to the small sample size) however the remanence parameters indicate an increase in the proportion of remanance carrying minerals relative to the fine and medium sand fractions (Table 5.3.4). The presence of both ferrimagnetic minerals and canted-antiferromagnetic minerals is indicated by the Soft IRM and HIRM parameters.

The magnetic signals generated in the El Saltador sub-reach indicate the material has been sourced from significant distances upstream and from local hillslope erosion and incision of the channel into weak lithological units. The signal is complex and must be regarded in terms of particle-size of both the terrace sediments and the source bedrock.

5.3.3.3 Magnetic Analysis: Basin-wide trends?

Analysis of the fine sediment (<2mm) preserved within the terrace units across the drainage basin was most thorough on the deposits associated with terraces C and D, preservation of terrace A and B being extremely patchy and limited. Basin-wide trends would be most clearly represented via analysis of magnetic variation across the basin for terraces C and D. Figures 5.3.8 A, B, C and D demonstrate the basin-wide trends in the 4 magnetic concentration parameters analysed on a particle-size basis in the current study for terrace stage C. Figure 5.3.8 a highlights the variation in peak χ_{LF} across the drainage basin. There is some evidence across the basin to suggest limited downstream fining of the grain size responsible for carrying the peak χ_{LF} signal. There is some suggestion of a downstream fining within the Lucainena sub-reach, as the χ_{LF} signal is generated in the coarse sand and appears to be winnowed into the medium sand downstream. It is not possible to assess how significant this value is as there is only one fragment of terrace C preserved. Downstream of the tributary junction with the Rambla Honda no terrace C deposits are preserved to analyse the impact of the signal sourced along the Rambla Honda. It is however, likely that downstream of the junction the signal would be



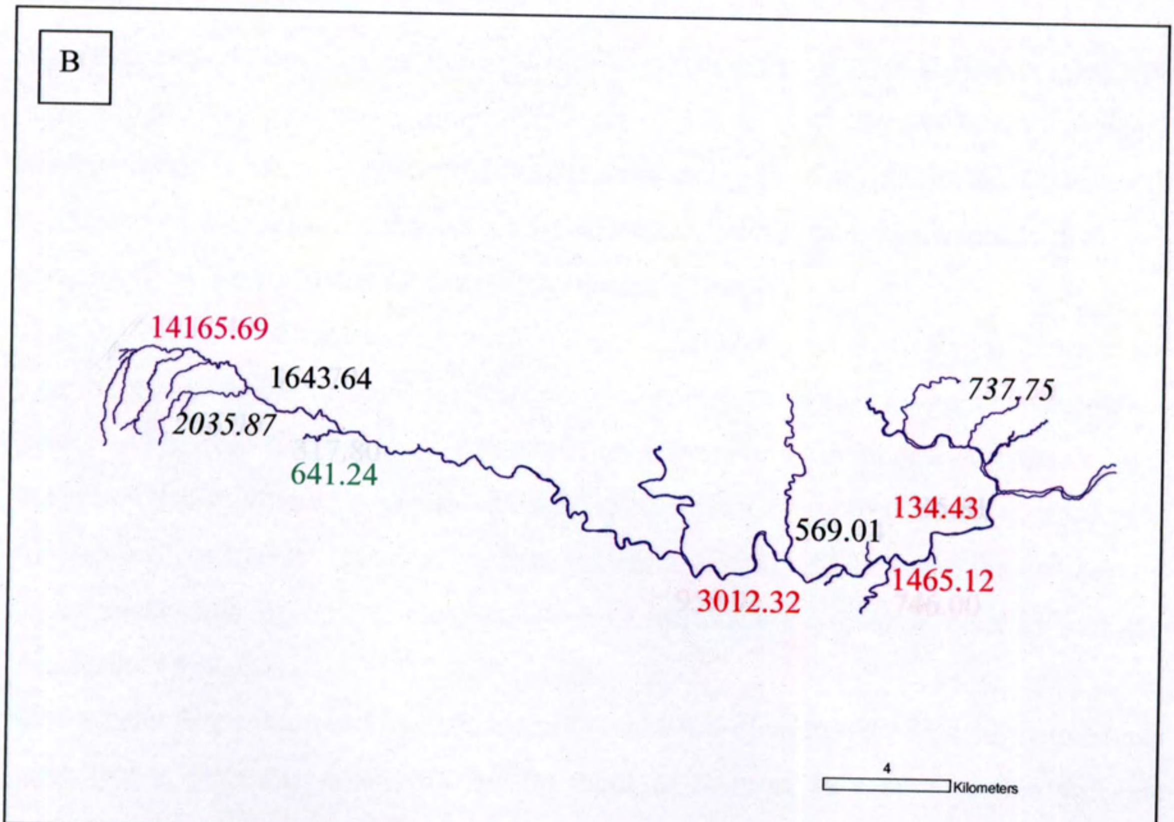


Figure 5.3.8 A and B. χ_{LF} and SIRM: basin-wide variation in terrace C. Particle size key as Table 5.3.1, magnetic units as Table 5.3.1. See text for explanation.

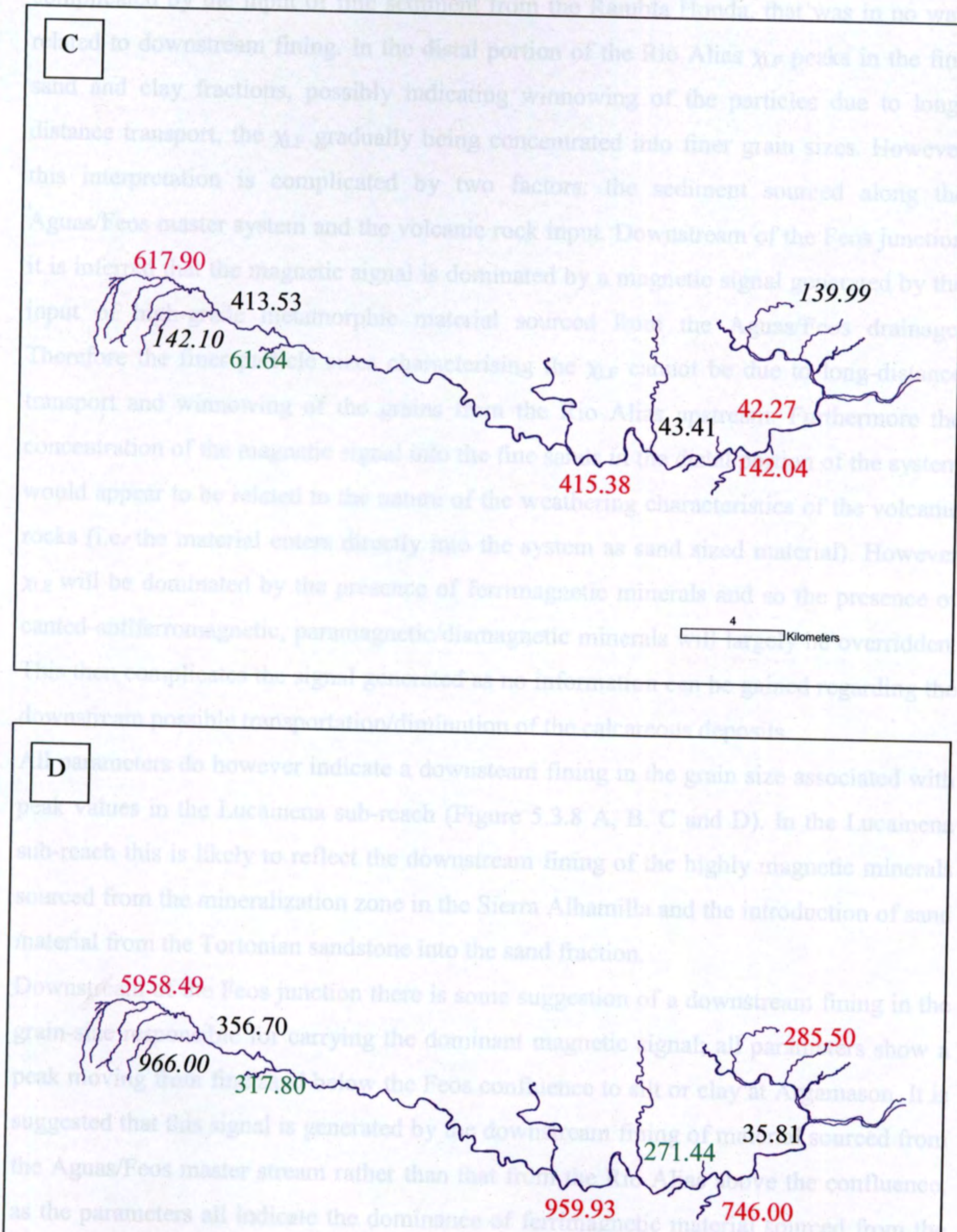


Figure 5.3.8 C and D. HIRM and Soft IRM: basin-wide variation in terrace C. Particle size key as Table 5.3.1, magnetic units as Table 5.3.1. See text for explanation.

complicated by the input of fine sediment from the Rambla Honda, that was in no way related to downstream fining. In the distal portion of the Rio Alias χ_{LF} peaks in the fine sand and clay fractions, possibly indicating winnowing of the particles due to long-distance transport, the χ_{LF} gradually being concentrated into finer grain sizes. However this interpretation is complicated by two factors: the sediment sourced along the Aguas/Feos master system and the volcanic rock input. Downstream of the Feos junction it is inferred that the magnetic signal is dominated by a magnetic signal generated by the input of high-grade metamorphic material sourced from the Aguas/Feos drainage. Therefore the finer particle sizes characterising the χ_{LF} cannot be due to long-distance transport and winnowing of the grains from the Rio Alias upstream. Furthermore the concentration of the magnetic signal into the fine sands in the distal portion of the system would appear to be related to the nature of the weathering characteristics of the volcanic rocks (i.e. the material enters directly into the system as sand sized material). However χ_{LF} will be dominated by the presence of ferrimagnetic minerals and so the presence of canted-antiferromagnetic, paramagnetic/diamagnetic minerals will largely be overridden. This then complicates the signal generated as no information can be gained regarding the downstream possible transportation/diminution of the calcareous deposits.

All parameters do however indicate a downsteam fining in the grain size associated with peak values in the Lucainena sub-reach (Figure 5.3.8 A, B, C and D). In the Lucainena sub-reach this is likely to reflect the downstream fining of the highly magnetic minerals sourced from the mineralization zone in the Sierra Alhamilla and the introduction of sand material from the Tortonian sandstone into the sand fraction.

Downstream of the Feos junction there is some suggestion of a downstream fining in the grain-size responsible for carrying the dominant magnetic signal; all parameters show a peak moving from fine sand below the Feos confluence to silt or clay at Argamason. It is suggested that this signal is generated by the downstream fining of material sourced from the Aguas/Feos master stream rather than that from the Rio Alias above the confluence, as the parameters all indicate the dominance of ferrimagnetic material sourced from the Aguas/Feos system.

In the distal Argamason and El Saltador sub-reachs it is clear that the ferrimagnetic signal generated is generally dominated by the input of material sourced from the volcanic rocks, and as such it is difficult to suggest any real downstream diminution as this material enters directly into the sand fraction. However HIRM (indicating canted-antiferromagenetic minerals) in terraces A and B in the El Saltador sub-reach, does

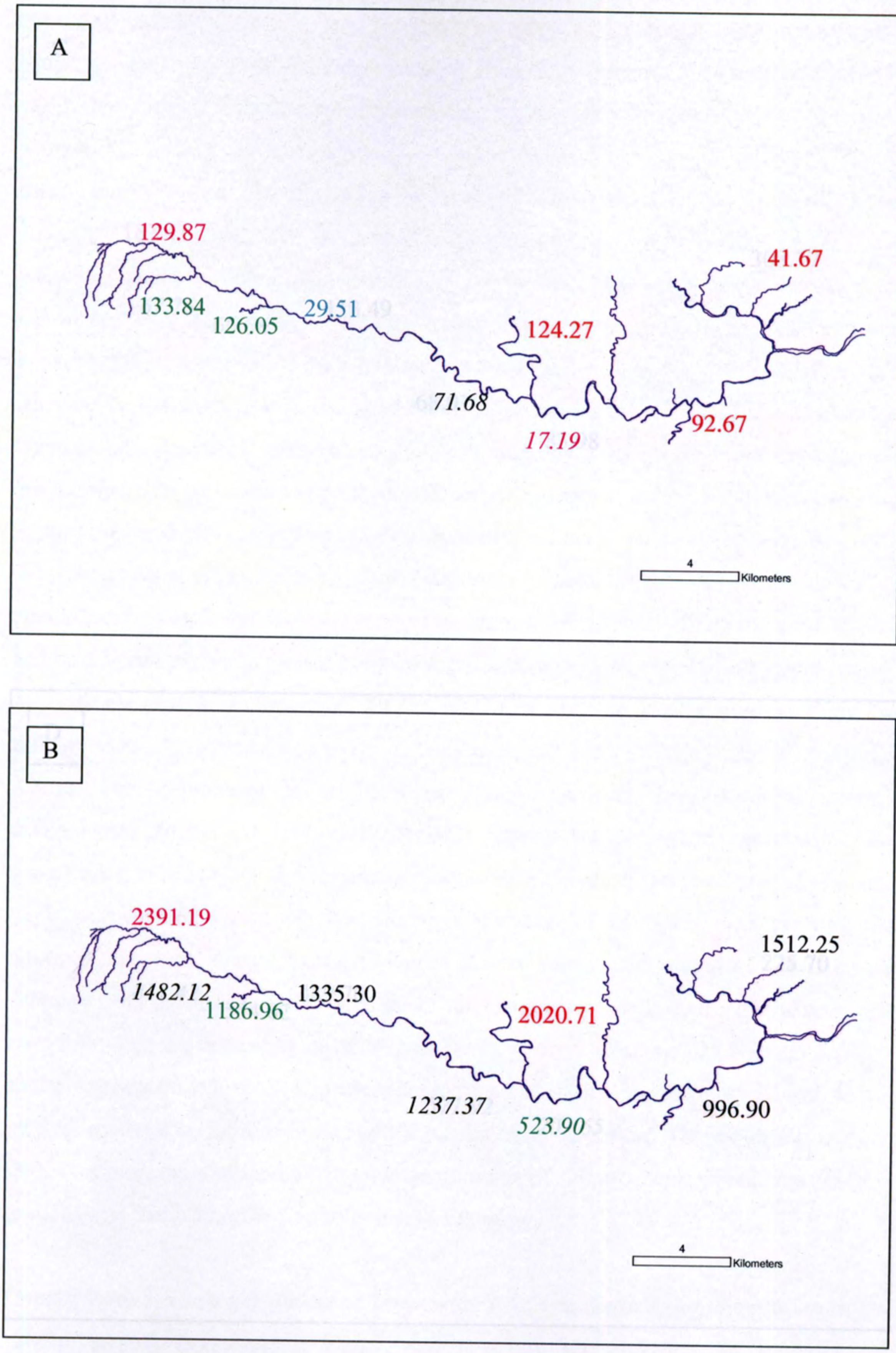


Figure 5.3.9 A and B. χ_{LF} and SIRM: basin-wide variation in terrace D. Particle size key as Table 5.3.1, magnetic units as Table 5.3.1. See text for explanation.

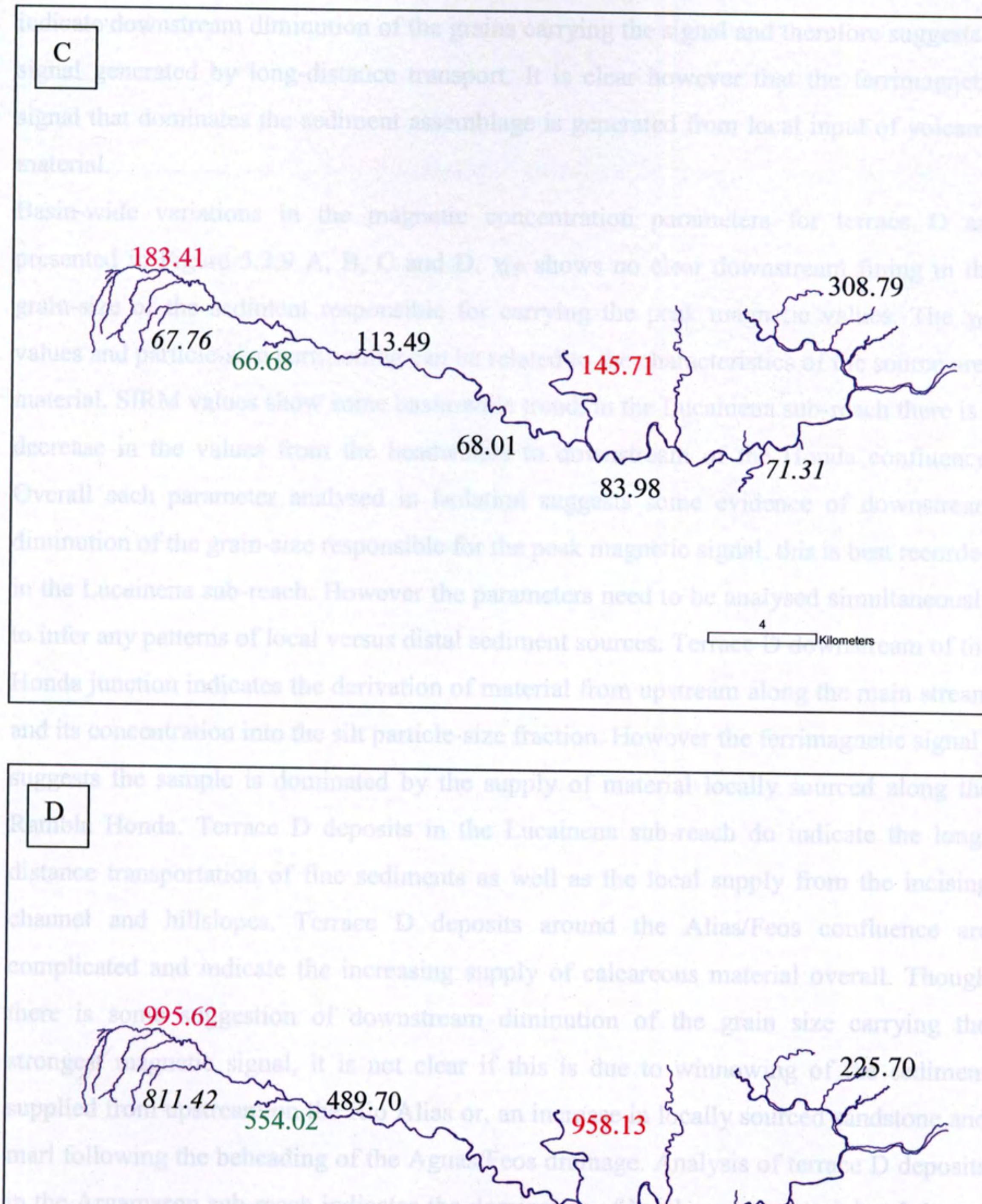


Figure 5.3.9 C and D. HIRM and Soft IRM: basin-wide variation in terrace D. Particle size key as Table 5.3.1, magnetic units as Table 5.3.1. See text for explanation.

indicate downstream diminution of the grains carrying the signal and therefore suggests a signal generated by long-distance transport. It is clear however that the ferrimagnetic signal that dominates the sediment assemblage is generated from local input of volcanic material.

Basin-wide variations in the magnetic concentration parameters for terrace D are presented in Figure 5.3.9 A, B, C and D. χ_{LF} shows no clear downstream fining in the grain-size of the sediment responsible for carrying the peak magnetic values. The χ_{LF} values and particle-size partitioning can be related to the characteristics of the source area material. SIRM values show some basin-wide trend, in the Lucainena sub-reach there is a decrease in the values from the headwaters to downstream of the Honda confluence. Overall each parameter analysed in isolation suggests some evidence of downstream diminution of the grain-size responsible for the peak magnetic signal, this is best recorded in the Lucainena sub-reach. However the parameters need to be analysed simultaneously to infer any patterns of local versus distal sediment sources. Terrace D downstream of the Honda junction indicates the derivation of material from upstream along the main stream and its concentration into the silt particle-size fraction. However the ferrimagnetic signal suggests the sample is dominated by the supply of material locally sourced along the Rambla Honda. Terrace D deposits in the Lucainena sub-reach do indicate the long-distance transportation of fine sediments as well as the local supply from the incising channel and hillslopes. Terrace D deposits around the Alias/Feos confluence are complicated and indicate the increasing supply of calcareous material overall. Though there is some suggestion of downstream diminution of the grain size carrying the strongest magnetic signal, it is not clear if this is due to winnowing of the sediment supplied from upstream on the Rio Alias or, an increase in locally sourced sandstone and marl following the beheading of the Aguas/Feos drainage. Analysis of terrace D deposits in the Argamason sub-reach indicates the dominance of local source material and do not suggest material is sourced from significant distances upstream. The magnetic analysis does however, once again indicate the partitioning of the magnetic signal into discreet particle-size fractions reflecting source-area lithology.

Overall there is some suggestion of basin-wide trends in downstream diminution of the grains carrying the magnetic signal, and therefore some element of long-distance transport of the fine sediment load is indicated when all the parameters are considered together. However, the magnetic analysis largely overrides the contribution of paramagnetic and diamagnetic minerals, and it is these paramagnetic/diamagnetic minerals that constitute a large portion of the available sediment supply. Furthermore where ferrimagnetic minerals dominate the assemblage the signal generated by canted-antiferromagnetic minerals will be subdued. Therefore in order to accurately determine the sediment source of the fine sediment load petrological and SEM analysis would have to be performed alongside the magnetic analysis to assess the contribution of the carbonate/quartz-dominant sandstones and limestones.

5.3.4 Provenance Synthesis of the Terrace Sequence

5.3.4.1 Introduction

Analysis of the provenance characteristics of the terrace sequence is presented in Sections 5.3.2 and 5.3.3. The provenance patterns indicated by the clast analysis and the magnetic analysis will be discussed below on a sub-reach scale.

5.3.4.2 Provenance Variation

a) The Lucainena Sub-Reach

The coarse sediment assemblage preserved in terrace A remnants in the headwaters of the Lucainena sub-reach display a dominance of the Alpujarride complex (including mineralization-zone rock) as the source area for both terrace A remnants is the Sierra Alhamilla. Terrace B deposits vary across the sub-reach reflecting the supply of material from both the flanks of the Sierra Alhamilla and the Neogene basin-fill as incision and channelisation begins. At the head of the basin the assemblage is dominated by clasts derived from the Alpujarride complex but downstream (above the Honda confluence) the proportion of sandstone has increased due to channel incision into the easily eroded Tortonian rocks. Downstream of the tributary junction with the Rambla Honda the main stream clast assemblage records the input of material from upstream on the main channel and from the Rambla Honda. The clast analysis indicates both local supply of sediment (particularly when the channel is incising into relatively weak rocks i.e. the Tortonian sandstone) and sediment supply from the headwater areas indicated by the presence of mineralization rock.

Terrace C deposits on the Rambla del Penoncillo record a different clast assemblage than terrace B deposits in the same area. The assemblage contains a greater proportion of basin-fill rocks and particularly reef limestones sourced to the north of the river. The variation between the deposits reflects the loss of tributary drainage sourced immediately to the south, in the area of Lucainena village (i.e. Alpujarride complex), and the resultant increased proportion of the drainage area of the Rambla del Penoncillo developed in the Neogene basin-fill rocks. The Lucainena village tributary was the aggressive capturing drainage and the tributary developed only after terrace B aggradation. The clast assemblage of terrace C in the Lucainena valley is dominated by Alpujarride material due to the rapid incision of the channel through the basin-fill sandstones de-stabilising the hillslopes and introducing sediment from the flanks of the Sierra Alhamilla. This interpretation of hillslope input is different from the interpretation given for the suspended sediment load as it is characterised by sandstone material that the channel is incising into. Furthermore terrace C deposits downstream (above the Rambla Honda confluence) also indicate the dominance of Alpujarride material in the coarse sediment load. The hillslopes immediately to the south would have provided Alpujarride material, and the newly developed, and aggressive, Lucainena tributary would also be supplying abundant Alpujarride material to the system downstream due to the supply from the de-stabilised hillslopes. The clast assemblage indicates that the supply of material is dominantly from upstream and not by direct incision into the sandstone/reef limestone bedrock.

Terrace D deposits on the Rambla del Penoncillo indicate the increase in supply of material from the headwaters in the Sierra Alhamilla and a decrease in supply of reef limestones from the hillslopes to the north. After the shutting off of drainage from the south direct incision into the sandstone and limestone initially dominated the sediment supply, however the downstream transportation of material from the Sierra Alhamilla was re-established during aggradation of terrace D. Terrace C deposits downstream of the confluence of the main stream and the Rambla Honda indicate a similar pattern as the modern channel Alpujarride material supplied along the Rambla Honda dominating the assemblage, and therefore local sediment sourcing is inferred.

Magnetic analysis of the suspended sediment was carried out on terrace deposits associated with terrace stages C and D. On the Rambla del Penoncillo magnetic analysis of the terrace C deposits indicates the presence of Alpujarride-derived fine material supplied from c.6km upstream. The assemblage indicates the presence of minerals sourced from the mineralization zone on the flanks of the Sierra Alhamilla. The terrace C deposits on the Lucainena village tributary do not display the same fine sediment load characteristics, instead the magnetic analysis indicates the sediment is derived from the sandstone and marl cut into by the channel. This interpretation is likely as the sandstones liberate fine sediment quickly and the material sourced from the adjacent hillslopes is relatively resistant and would not be broken down to fine particles so quickly. Terrace D deposits on the Rambla del Penoncillo suggest a change in the dominant material in the fine sediment load. This is due to either a decrease in the proportion of magnetic material supplied from the headwaters in the Sierra Alhamilla or an increase in the proportion of basin-fill material in the deposit. It is likely to be a combination of the two, as, if the minerals associated with the mineralization zone were present even in small amounts, they would dominate the magnetic signal. Consequently on the Rambla del Penoncillo the sediment source of the fine-grained material has varied through the development of the system. On the Lucainena village tributary the magnetic signal generated is complex and little can be inferred relating to sediment provenance. It can be inferred however that the sediment released by the incision into the Tortonian sandstones is delivered to the medium sand particle-size fraction. Downstream at the confluence with the Rambla Honda terrace C deposits above the confluence indicate an increase in the proportion of Neogene basin-fill calcareous sources and a downstream fining of the grains carrying the dominant magnetic signal. However the downstream fining is likely to be a function of the increasing proportion of fine-grained basin-fill material entering into the system rather then a diminution effect on the magnetic minerals recorded upstream. The fine sediments associated with terraces C and D on the Rambla Honda can only be sourced from the Alpujarride complex therefore magnetic characteristics of the fine sediment generated can be indicated. The magnetic analysis indicates that the sediment liberated from the Alpujarride schist is focused into the clay particle-size fraction. Consequently downstream of the Honda junction terrace D deposits display similar values to those on the Rambla Honda and can be interpreted as being dominated by sediment supplied from the Rambla Honda. The concentration of canted-antiferromagnetic minerals in the silt fraction however, indicates material supplied is being supplied from upstream on the main channel and concentrated into the silt-particle size fraction.

The clast and magnetic analyses indicate that the terrace sequence in the Lucainena sub-reach records both long-distance transport and local supply of material, in both the coarse and fine sediment fractions. The clast analysis indicates that coarse sediment is supplied from both upstream sources and local hillslope sources and is often related to bedrock lithology and/or source area variation. The fine sediment analysis exhibits similar patterns, both long-distance transport and local supply of sediment is indicated in different parts of the system and this can be linked to source area change over time (via river capture) and the lithology of the bedrock into which the stream was incising at the time.

b) The Polopos Sub-Reach

Terrace A and B deposits, preserved at the head of the sub-reach downstream of Polopos, indicate the input of coarse material from the transverse reach of the Rio Alias upstream of Polopos, incised into the Alpujarride complex and reef limestone. Terrace B deposits indicate a high proportion of the coarse material was supplied from upstream (i.e the Alpujarride complex) suggesting increased transportation of the clasts from the distal portion of the Lucainena sub-reach. Terrace B deposits on the Rambla de los Feos also indicate both local and distal sediment source areas of the coarse bedload material. The terrace C deposits on both the Rio Alias downstream of Polopos and on the Rambla de los Feos, present similar assemblages to the terrace B deposits suggesting no variation in source area material between the terrace stages on either the Rio Alias (upstream of the confluence) or the Rambla de los Feos. Terrace C deposits downstream of the confluence of the Rambla de los Feos and the Rio Alias, indicate significant input from the Rambla de los Feos, though an increased proportion of basin-fill material indicates the local incision of the channel into Neogene basin-fill rocks. Terrace D downstream of Polopos indicates similar sediment source provenance as terraces B and C, though the input of calcareous material indicates increased local input and the presence of mineralization rock indicates the downstream transportation of coarse material sourced in the Lucainena headwaters. On the Rambla de los Feos and the Rio Alias downstream of the Feos junction terrace D deposits record the loss of hornblende schist sourced from the Sierra de los Filabres to the north and therefore identify the stage of drainage evolution following the be-heading of the Aguas/Feos master drainage. The proportion of the Alpujarride complex increases as the headwaters of the Rambla de los Feos would be dominantly sourced in the Sierras Alhamilla/Cabrera and to a lesser extent basin-fill rocks in the lower reaches. The coarse sediment assemblage on the lower Rio Alias indicates the shutting off of the distal source areas following the capture and the increasing importance of local sediment supply.

Magnetic analysis on the terrace B deposits downstream of Polopos suggests that the primary source of the fine sediment is in the Lucainena sub-reach. The magnetic signal generated is much stronger than that of the modern channel sediments and the grains carrying the dominant magnetic signal are fine and medium-sized sands. It is suggested the sands are sourced in the mineralization zone and there is downstream diminution of the size of the grains derived from the mineralization rocks. Terrace C deposits on the Rio Alias below the Feos junction also have a stronger magnetic component than sediments from the same location in terrace D and in the modern channel. The loss of the high-grade Filabres metamorphics, following the Aguas-Feos capture, between terrace C and D is indicated by the magnetic analysis. Terrace D deposits on the Rio Alias above the Feos confluence indicate the same magnetic properties as terrace B and therefore indicate possible long-distance transport of fine sediment supplied from the Lucainena sub-reach. However, there is also the indication of an increase in the proportion of locally supplied sandstone and marl (represented by the HIRM peak in the fine sands). Terrace D indicates the presence of fine-grained material sourced both locally and from significant distances upstream. On the Rambla de los Feos terrace D sediments are different from those on the Rio Alias above the junction and indicate input from the Alpujarride complex and the local sandstone into which the channel is incised in its lower reaches. The input of sandstone material also appears to be greater on the Rambla de los Feos than on the Rio Alias upstream, supporting the idea of significant long-distance transport of the fine material in terrace D on the Rio Alias above the Feos confluence. Downstream of the confluence the magnetic properties of terrace D are complicated and may indicate an increase in the supply of local carbonate rocks, gypsum and quartz minerals as the magnetic signal is somewhat diluted.

Clast analysis on the terrace deposits of the Polopos sub-reach suggests the supply of coarse material is both from local incision of the bedrock and from long-distance transport of material from upstream. Basic magnetic analysis also indicates both local and distal sediment source areas, though the signal is complicated and needs further independent analysis to support the interpretation.

c) The Argamason Sub-Reach

Terrace B deposits preserved in the central portion of the Argamason sub-reach indicate the bedload material is sourced both by local incision into the basin-fill rocks and by long-distance transport of material along the Aguas/Feos master drainage. Terrace C1 (the equivalent of terrace C upstream) displays the same general characteristics as terrace B on the Feos, and of terrace C below the Feos junction. Again this indicates the combination of both a distally and locally derived clast assemblage, with the hornblende schist component indicating a sediment source from the north-west portion of the Sorbas basin. Terrace deposits associated with terrace stage C2 preserve a coarse sediment assemblage across the sub-reach, and all the deposits record a component of hornblende schist that is c.5% of the total. It is inferred the hornblende schist is sourced from re-working of terrace C1 deposits in the sub-reach due to tectonically driven lateral migration and incision. Furthermore the terrace C2 deposits show variation in the proportions of the other lithological units. At the head of the sub-reach, at the nickpoint, the assemblage is dominated by Alpujarride material indicating input from the Arroyo Gafares as are the deformed sediments downstream of Argamason. Further downstream C2 deposits display an increase in the local input of coarse material via the clearly recognized volcanic clasts. Terrace D deposits across the sub-reach signal very little or no input of hornblende schist. At the head of the sub-reach (at the nickpoint) terrace D deposits are well mixed indicating sediment is being supplied via the Arroyo Gafares (Alpujarride complex) and from direct incision into Neogene basin-fill rocks. Downstream (both above and below the Palmerosa tributary) the proportion of Alpujarride material has decreased and c.60-70% of the sediment load is derived from basin-fill or volcanic rocks. Therefore the coarse sediment load at both the head of the sub-reach and the distal portion of the sub-reach, indicates dominant local sediment delivery to the system.

Analysis of the fine sediment load is difficult in the Argamason sub-reach due to the lack of fine material preserved. Where sediment was available, C1 deposits are magnetically weaker than the terrace C deposits below the Feos junction but similar to those preserved in the modern channel below the Palmerosa tributary. During the evolution of terrace stage C1 the channel belt had began to incise laterally and so it was eroding local material, the dominant bedrock upstream of the Palmerosa tributary is the Cuevas Viejas sandstone and thus would supply fine grained material to the channel (similar to the modern system). Therefore it is implied that the decrease in the magnetic signal of the terrace C1 deposits relative to the terrace C deposits upstream is likely to reflect the increase in local supply of fine-grained sediment from the hillslopes due to the lateral incision of the channel. The decrease in the magnetic signal may also be partly due to the loss of the hornblende schist within the fine component. Terrace C2 deposits are significantly different from the C1 deposits with a much stronger magnetic signal apparent, and it is inferred that this reflects input from the eroded volcanic rocks that form the valley-wall backing this terrace unit. The volcanic rocks, as it has already been noted, do quickly disintegrate into the fine sediments on weathering. The signal is somewhat stronger than that generated in the modern channel and this may be related to the input of calcareous material diluting the magnetic signal of the modern channel (as indicated by the presence of carbonate grains on the SEM analysis). The magnetic signal generated by terrace D deposits is complex, but it can be inferred that the erosion and supply of local material (both the volcanic rocks and the Cuevas Viejas sandstone) is indicated in the magnetic analysis. Similarly to the terrace C2 deposits the magnetic signal is stronger than that generated by the modern channel, and this may reflect the fact that the modern channel is supplied increasingly by sandstone and marls whilst the terrace deposits received more volcanic input. Alternatively the stronger magnetic signal of the fine sediments in the terraces below Argamason village, may be related to the re-working and mobilising of hornblende schist material during the lateral incision of the channel during terrace stages C1-D.

The pre-capture terraces (C1 and B) indicate a combination of both distal and proximal sediment source areas of the coarse sediment assemblage. The later terrace sequence (C2-D) and the modern channel increasingly indicate the dominance of local sediment supply. The fine sediments preserved generally indicate the dominance of local sediment supply through terraces C1-D reflecting local incision of the channel (driven by both tectonics and climate). Terrace stage C1 preserves a coarse sediment assemblage associated with both local and distal sediment sources whilst the suspended sediment load does not indicate this feature, though petrological analysis would be needed to support this assertion. The terrace deposits in the Argamason sub-reach indicate subtly different provenance patterns than the terraces in the other sub-reachs, and it can be inferred that this is related to local tectonically driven incision of the channel into bedrock altering the source of the material supplied to the fluvial system.

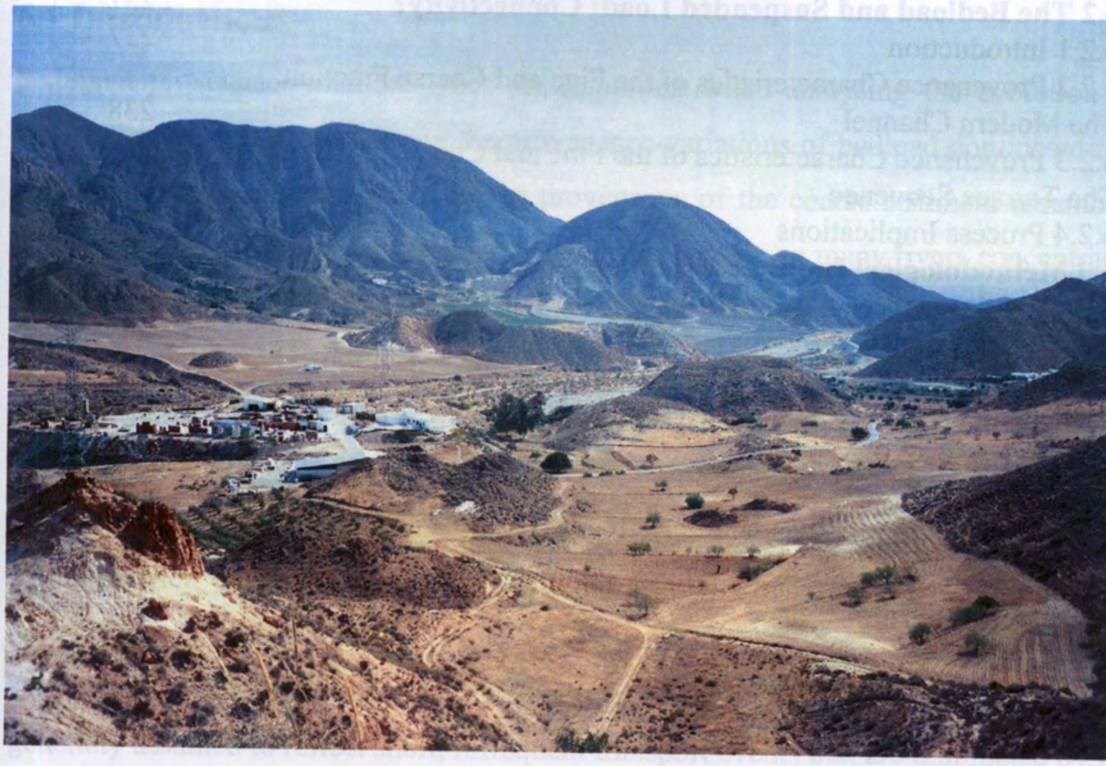
d) The El Saltador Sub-Reach

At the head of the sub-reach terrace A deposits reflect a mixed bedload signal with a significant proportion of the coarse sediment transported from distal upstream sources (i.e. Alpujarride schist sourced from the Arroyo Gafares, and hornblende schist from the Aguas/Feos master stream). Terrace B sediments preserved downstream at the entrance to the large abandoned meander loop also indicate a large component of the bedload is transported from significant distances upstream. Basin-fill material and hornblende schist represent material transported downstream from the Argamason sub-reach, the Alpujarride complex however, is likely to be sourced from the Rambla del Saltador. At the exit of the meander loop the proportion of hornblende schist has decreased and the proportion of volcanic material has increased; indicating an increased supply of sediment from local hillslopes. The increase in the proportion of volcanic clasts is due to the incision of the abandoned meander loop into the volcanic bedrock material. Terrace B deposits on the Rambla del Saltador reflect the near dominance of the Alpujariride complex in the headwater area. Terrace C preserved immediately upstream of the modern Alias/Saltador junction (on the south side of the stream) displays a mixed bedload similar to that of terrace A, but with an increased proportion of volcanic clasts. The presence of the hornblende schist and the Cuevas Viejas sandstone indicates sediment sourced from significant distances upstream, whilst the volcanic component indicates local erosion. Downstream, in the coastal portion of the Rio Alias the sediment assemblage of terrace C is dominated by the Alpujarride complex, most likely sourced from the Rambla del Saltador. The presence of reef limestone and hornblende schist however, indicates a component of the coarse sediment assemblage is sourced from significant distances upstream. Terrace D sediments in the same location record no hornblende schist, and therefore reflect the be-heading of the Aguas/Feos drainage. Furthermore, relative to terrace C there is decrease in the proportion of Alpujarrride material and an increase in the volcanic/basin-fill component. This is indicative of an increase in material supplied from the Rio Alias from the area upstream and from local incision into the volcanic bedrock.

Magnetic analysis of terrace A deposits at the head of the sub-reach does not indicate a local supply of fine sediment. Elsewhere in the drainage basin, and on the modern channel the input of volcanic material (co-incident with the outcrop of volcanic material along the channel/hillslopes) is indicated by a strong spike in the value of the magnetic parameters, and this is not indicated in the terrace A sediments. The magnetic signal generated may relate to the long-distance transport of grains sourced from the Aguas/Feos master stream (similar to the signal generated by terrace C deposits below the Feos junction). Magnetic analysis of the terrace B deposits at the entrance to the abandoned meander loop indicates the input of local volcanic material (concentrated into the fine sand fraction) into the fine sediment assemblage. As indicated previously, where ferrimagnetic minerals are present they dominate the magnetic signature, and consequently the magnetic signal in terrace B is dominated by the volcanic material. HIRM values do however suggest the input of canted anti-ferromagnetic minerals into the silt fraction. It cannot be determined if the minerals are sourced from the sandstones and marls or from the calk-alkaline volcanic rocks. Petrological analysis of the deposits would be needed to determine the possible source of the canted-antiferromagnetic minerals. Terrace C deposits at the head of the sub-reach (at the modern nickpoint) indicate the input of material from upstream as there is no volcanic signature present. The material is likely however to be sourced in the Cuevas Viejas sandstone upstream (and in particular a quartz-rich lithofacies), as there is no indication of possible long-distance transport of magnetic minerals as in terrace A. Terrace C and D deposits on the Rambla del Saltador exhibit variation between the units. Both units are dominated by the presence of ferrimagnetic grains sourced in the Alpujarride complex in the Sierra Cabrera, but the terrace D deposits indicate an increase in the proportion of the ferrimagnetic and canted-antiferromagnetic minerals in the silt fraction. The signal is complex but it can be assumed (due to the source area lithological characteristics) that the sediment supplied is sourced from the Alpujarride complex. The coarse sediment assemblage in the older terraces (A-C) indicates both local and distal sediment sources. The magnetic analysis of the fine sediment assemblage of terraces A-C also indicates both local and distal sediment sources and therefore indicates long-distance transport of material.

Overall the provenance characteristics of both the coarse and fine sediment assemblages indicate a combination of locally supplied and distally sourced material input to the sediment load at any one point. There are sub-reach complications (related to lithological characteristics) and delivery of some bedrock material is focused into a particular particle-size fraction of the channel load. However there is significant evidence to suggest that the delivery of locally sourced material increases as the system evolves and incises increasingly into bedrock. The degree of similarity between the coarse and fine sediment assemblage also varies on both temporal and spatial scales due to the increasing importance of locally supplied sediment as the system evolves and the lithological characteristics of the bedrock. The similarity of the provenance signal generated by the coarse and fine sediment assemblage and the changing proportion of local and distal sediment sources through time will be assessed in the next chapter.

Chapter 6
Methodological Implications: Provenance Ascription



Meander loop development at the coast.

Chapter 6
Methodological Implications: Provenance Ascription

Chapter 6
Methodological Implications: Provenance Ascription

6.1 Introduction

Sediment provenance characteristics are important when analysing the evolution of a fluvial system. When considering the provenance variations of bedload dominated rivers it is important to consider not only the provenance of the coarse sediment assemblage, but also the fine sediment assemblage. Provenance studies on many rivers concentrate on either the coarse or the fine sediment characteristics. Previous studies, for example in the Pindus Mountains, Greece (Woodward, 1990; Woodward et al., 1992) highlight the importance of establishing provenance characteristics of both the coarse and fine sediment assemblages in order to fully reconstruct the palaeoenvironmental conditions of fluvial system development. Therefore it is of significant interest to establish reliable methodologies of sediment source ascription for both the coarse and fine sediment assemblages.

The coarse sediment assemblage (generally representing the bedload component) is generally assumed to reflect short, infrequent transport events that are dominated by local sediment sources and therefore produce a provenance signal dominated by local sediment supply. The fine sediment fraction (largely representative of the suspended sediment load) can be sourced locally from bedrock material that liberates fine particle sizes, from the attrition of bedload sediment from further upstream, or from catchment-wide fine sediment sources. The transport paths of the suspended sediment can therefore be diffuse and can represent frequent, long-distance transport of the sediment assemblage-consequently producing a complex provenance signal.

6.2 The Bedload and Suspended Load: Connectivity?

6.2.1 Introduction

The analysis of both the modern channel and the terrace sequence via clast lithological/shape/size analysis and laboratory analysis (Environmental Magnetism, SEM and petrological analysis) allows the relationship between the two transportational processes to be examined. Furthermore the applicability of the methods of provenance ascription employed can be assessed.

6.2.2 Provenance Characteristics of the Fine and Coarse Fraction: The Modern Channel

The results presented in Chapter 5.2 display a correlation between the provenance characteristics of the coarse and fine sediment load. All provenance parameters suggest a strong local-bedrock signal implying the dominant source of material is from local channel incision. In the Lucainena sub-reach clast provenance characteristics are dominated by local sediment supply. The importance of tributary junctions is also emphasised in the coarse assemblage, the material sourced from the Rambla Honda dominating the sediment assemblage downstream of that tributary junction. The suspended sediments throughout the sub-reach also suggest the dominance of locally derived sediment input. Furthermore the suspended sediment assemblage indicated by all proxy measurements, also highlights the dominant input of material from the smaller tributary streams at the confluence zones.

The provenance signal is complicated by the degree of resistance to mechanical erosion of the bedrock sources, and the marine sands and marls can be seen to concentrate into the suspended sediment fraction. Alpujarride schists interestingly concentrate into both the coarse and fine sediment loads due to the nature of the mechanical breakdown of the material. There is a small amount of variation between the results presented for the magnetic analysis and for the petrological/SEM analysis. The presence of highly magnetic grains sourced from the iron ore slag heaps indicated by the magnetic analysis is not picked up by the petrological/SEM analysis. Furthermore, magnetic analysis does not identify the subtle differences in the carbonate content of samples taken on the two adjacent streams in the Lucainena sub-reach, the Rambla del Penoncillo and the Lucainena tributary; this will be discussed on detail in section 6.3.

The results obtained for both size fractions are generally in agreement indicating local sediment supply is dominant in the Lucainena sub-reach.

In the Polopos sub-reach clast lithological analyses indicates the dominance of the local supply of bedload and the importance of local source area lithology. At the head of the sub-reach the coarse component is sourced from the Alpujarride unit (and in particular the schist component) rather than in the reef limestone within which the canyon is developed. This pattern reflects the degree of resistance of the reef limestone bedrock to mechanical erosion. Downsystem the bedload component increasingly reflects locally sourced input from the surrounding hillslopes and from the material directly incised by the modern channel. At the tributary junction of the Rio Alias and the Rambla de los Feos it is difficult to infer the degree of input from each stream as the material carried along both streams is very similar. However the bedload component again indicates the input of local material dominating the sediment assemblage. The suspended sediment signal provided by the petrological/SEM analysis indicates the dominance of the Alpujarride complex on the Rio Alias upstream of the Feos confluence, therefore giving the same provenance indications as the coarse sediment assemblage. The lower Feos grain assemblage is similar to the Rio Alias upstream of the confluence reflecting the similar source areas, but there is an increase in the amount of Neogene basin-fill material represented by the calcareous sandstone. This subtle variation in the fine sediment load largely reflects the bedrock resistance to mechanical erosion. The Cuevas Viejas sandstone is easily eroded and concentrated into the sand fraction (reflected in the grain assemblage) whilst the reef limestone is more resistant to erosion and so is present initially largely in the clast assemblage. Downstream of the confluence the grain properties generally indicate that the assemblage is largely sourced from the Rio Alias and not the R. de los Feos, though this is difficult to establish definitively due to the similarity of the source areas. Magnetic analysis indicates a difference between the R. de los Feos and the main stem of the Rio Alias and also suggests the concentration of magnetic minerals into discreet particle-size fractions. Magnetic analysis supports the petrological/SEM analysis on the Rambla de los Feos indicating the partitioning of the Cuevas Viejas derived sands into the medium sand fraction. Downstream of the Feos junction magnetic analysis indicates the input of local material sourced from the marine marls into which the modern channel is incising. The coarse and fine sediments all indicate the dominance of local sediment supply to both the suspended and bedload material. However the fine sediment analyses in particular, highlight the importance of the bedrock lithological properties in terms of sediment generation and concentration into particular particle size fractions.

In the Argamason sub-reach clast analysis suggests the dominance of locally supplied coarse material to the bedload assemblage in the upper part of the sub-reach from along the main channel of the Rio Alias and from the Arroyo Gafares tributary. In the lower portion of the sub-reach the input of volcanic material, the resistant sandstone and hornblende schist (re-worked from the terrace deposits) further indicates the very local input of material to the coarse sediment assemblage. Moving downstream away from the

Arroyo Gafares and the input of Alpujarride material, the clast assemblage records an increasing amount of basin-fill material, however, the Alpujarride component is dominant throughout indicating the importance of material sourced from the tributary system. Petrological analysis at the head of the sub-reach indicates much localised input from the Neogene basin-fill rocks. Downstream at the distal portion of the Argamason sub-reach, surprisingly the petrological/SEM analysis indicates the dominance (and increase) in the proportion of Alpujarride material. This is a pattern somewhat different from those presented elsewhere in the basin indicating the sediment source of the fine grained material is dominated by Alpujarride input c.5km upstream. This indicates a variation in the sediment source between the coarse and fine sediment loads in the Argamason sub-reach. Magnetic analysis of the suspended material throughout the sub-reach suggests the magnetic signal is dominated by the input of the volcanic material, and is not reflecting the long-distance input of the Alpujarride complex indicated by the petrological/SEM analysis. The magnetic signal generated by the volcanic material is stronger than that of the Alpujarride material and so the identification of the latter component is impossible within the sample even though proportionally the Alpujarride complex may dominate the assemblage.

In the El Saltador sub-reach the Rio Alias drains a major area of volcanic rock and this is reflected in the clast content of the Rio Alias upstream of its confluence with the Rambla del Saltador. At this location the volcanic rocks are initially broken down into the coarse component as they are sourced immediately adjacent to the channel, however after a small amount of transport and therefore abrasion the clasts degrade into fine sediment. The signal generated along the Rambla del Saltador is different and again reflects local input of coarse material. Downstream of the confluence the coarse sediment assemblage is dominated by sediment input from the Rambla del Saltador, however there is limited input from the main stem of the Rio Alias upstream indicated by the small amounts of reef limestone and carbonate. As at other tributary junctions the smaller tributary joining the main stream contributes more sediment than the main stream. The grain assemblage indicated by petrological/SEM analysis on the Rio Alias above the confluence suggests local input of the volcanics and sandstone bedrock material dominating the sediment supply, with little evidence of long-distance transport from further upstream. Along the Rambla del Saltador, Alpujarride (including Quartz) material dominates the sediment assemblage and downstream of the Saltador junction the grain assemblage is also dominated by Alpujarride material. However the proportion of hornblende and other minerals suggests the input of volcanic material directly from the hillslopes incised by the modern channel. Magnetic analysis in the Saltador sub-reach is again dominated by the input of the distinct volcanic material. On the Rio Alias upstream of the Saltador confluence the magnetic signal is concentrated into the fine sand range. This reflects the mechanical weathering of the volcanic bedrock and concentration of the magnetic grains into the fine-sand fraction. On the Rambla del Saltador the signal generated is somewhat different with a lower magnetic signal concentrated into the silt fraction. Downstream of the Rio Alias/Saltador confluence the magnetic analysis suggests a mixed assemblage with volcanic grains dominating the signal as the main signal is carried in the fine sand fraction. However the absolute values are decreased and given the usual dominance of the magnetic signal generated by the volcanic minerals, this would indicate a high proportion of Alpujarride material. This interpretation would agree with the assemblage indicated by the petrological/SEM analysis. Sediment provenance analysis indicates that a local supply of material dominates the sediment supply in the El Saltador sub-reach, similar to the other sub-reachs.

All provenance indicators suggest the dominance of local sediment supply in both the bedload and suspended load of the modern channel. Furthermore analysis of the mean roundness and TND values from the headwaters to the coast indicate little evidence for long-distance transport of bedload material, but support the inference of local sediment supply dominating the sediment available to the fluvial system.

6.2.3 Provenance Characteristics of the Fine and Coarse Fraction: The Terrace Sequence

In the Lucainena sub-reach the clast assemblage associated with the early development of the fluvial system (terraces A and B) preserved across the basin suggest that the coarse material is sourced both form local incision into bedrock and from downstream transport of the clasts. Terrace C deposits preserved in the upper part of the basin on the Rambla del Penoncillo indicate a decrease in coarse material sourced from the Sierra Alhamilla hillslopes and an increase in locally sourced material resulting from the capture-related loss of drainage. The fine sediment load however indicates the input of sediment from significant distances upstream following the capture event. The terrace C deposits preserved at Lucainena village indicate that the fine sediment available was dominated by the bedrock within which the channel was directly incising at the time, but the material

supplied from the hillslopes of the Sierra dominates the coarse sediment assemblage. This suggests different processes are active on the two systems, however the variation between the streams can be explained by the lithological characteristics of the source rocks. The Lucainena system incises directly into Tortonian sandstone that is weakly consolidated and thus enters directly into the fine sediment assemblage. The Alpujarride complex (here dominated by meta-carbonate and mineralization rocks) is lithologically stronger and consequently needs to be transported greater distances to be broken down into the fine sediment load (as on the Rambla del Penoncillo). Terrace D deposits on the Rambla del Penoncillo suggest the clast assemblage is dominated by the input of material from upstream in the Sierra Alhamilla whilst the suspended sediment load indicates a more localised sediment input. This may indicate increased incision in the headwaters following the local capture event. Downstream of the Rambla Honda junction the sediment assemblage (both coarse and fine) indicates the dominant supply of material is from the tributary stream.
The provenance patterns of the terrace sequence indicate local and distal sources of both the coarse and fine sediment load. Variations in provenance through time can be attributed to new erosion into local bedrock sources and capture driven source-area changes. The lithological strength of the bedrock units also impacts the nature of the sediment generated into either the coarse or fine sediment fraction (i.e. Tortonian sandstone is liberated rapidly into the fine sediment load due to the uncohesive nature of the rock). Furthermore it is inferred that a general pattern of downstream rounding and decrease in the average grain size of the coarse sediment is demonstrated through the basin. It can be inferred as the fluvial system develops the stream incises and decreases its gradient, and as this occurs the local supply of material to both the coarse and fine sediment load increases.

In the Polopos sub-reach terrace A, B and C deposits demonstrate clast assemblages that indicate the dominance of long-distance bedload transport from both the Lucainena sub-reach and from the Sorbas basin (i.e. the Aguas/Feos master stream). Terrace C deposits on the Rio Alias below the Feos confluence also indicate the long-distance transport of bedload material (i.e. the hornblende schist), but the increasing importance of locally sourced material is also increasingly indicated. Downstream of the Feos confluence the coarse sediment assemblage suggests the dominance of material sourced along the Rambla de los Feos prior to the capture event in the Sorbas basin. Analysis of the fine

sediment assemblage of terrace B sediments upstream of the Feos junction and terrace C below the junction indicate that the magnetic signals in the fine sediment assemblages are dominantly sourced from long-distance transport of material from the Lucainena sub-reach and the Sorbas basin respectively. The signal generated is starkly different from that of the modern channel reflecting the change in the source area lithological properties from the ancient to the modern system. Terrace D deposits above the Feos confluence indicate the continuing supply of material from the Lucainena sub-reach, however the increasing amount of locally generated material is also indicated. Terrace D on the Rambla de los Feos and below the confluence, however indicates the dominance of locally sourced material in the coarse sediment assemblage, which is probably due to the be-heading of the Aguas/Feos master stream and incision into local material. The magnetic signal of the fine sediment assemblage is complicated in terrace D, though it can be inferred that upstream of the Feos confluence long-distance transport is indicated but on the Rambla de los Feos below the confluence, local input of fine sediments from the Cuevas Viejas formation is suggested.
The sediment assemblage across the Polopos sub-reach prior to the capture event (which followed the aggradation of terrace C) indicates the input of material from both upstream sources and by local incision of the stream into local bedrock. Terrace D (post-capture) on the Rambla de los Feos and on the Rio Alias below the confluence, indicates the dominance of locally generated coarse and fine sediment input to the fluvial system. Below the confluence the change to local input of material is likely to be primarily related to the be-heading of drainage sourced in the Sorbas basin. However, terrace D deposits upstream of the confluence indicate continuing long-distance transport of both coarse and fine material, though the input of locally sourced material is increasing and this increase can be seen to continue into the modern day system. The evolution of the system leads to incision, and again it can be inferred that as the system develops the input of local material to the system increases. The signal generated in the Polopos sub-reach is however, complicated and dominated by the capture event in the Sorbas basin and the be-heading of the Aguas/Feos master system.

The palaeoenvironmental evolution of the Argamason sub-reach is complicated by tectonic activity and as such there is little sediment preserved relating to terraces older than stage C. There is one outcrop of terrace B in the central portion of the Argamason sub-reach and the clast assemblage preserved indicates both local and distal sediment sources as does the preserved assemblage associated with terrace stage C1. Magnetic analysis of terrace C1 however, indicates a different assemblage from that of the equivalent terrace C upstream. It is inferred this is related to the local incision of the stream into bedrock material and the liberation of fine-grained sandstone (forced by tectonic activity). During terrace stage C2 local input of coarse material is indicated and it is due to the local incision of the channel belt into older local alluvium and bedrock, forced by tectonically induced base-level lowering. Magnetic analysis also indicates that the fine sediment load is sourced in local volcanic bedrock. The sediment assemblage is dominated by local input following terrace stage C1 (which also coincides with post-capture drainage). The signal in the Argamason sub-reach is complicated both by the capture-associated impact on drainage development and by local tectonic activity. Terrace D deposits across the sub-reach indicate the input of local material to the coarse and fine sediment assemblage. The geomorphic assemblage suggests that the major phase of Quaternary tectonic activity had ceased by terrace stage D and so the local supply of both coarse and fine sediment to the system cannot be attributed to tectonically forced lateral erosion of the stream into local bedrock material as indicated in terrace stage C2. It is inferred that the increasing importance of local supply to the sediment assemblage during the evolution of terrace D and the modern channel, is related to increasing local incision into bedrock due to the decreasing gradient of the river; as indicated elsewhere.

Terrace A in the El Saltador sub-reach preserved at the westwards limit of the sub-reach, indicates the long-distance transport of both the fine and coarse material. This is expressed by the abundance of hornblende schist, and to a lesser extent by the mean downstream increase in roundness of the clasts. Terrace B deposits reveal a slightly more complicated picture with the coarse assemblage at the head of the basin represented by a mixture of clast lithologies, some transported from significant distances upstream. The fine sediment assemblage though, indicates local input of the fine sediment load. At the exit of the large abandoned meander loop (associated with terrace B) the coarse sediment assemblage indicates an increase in the amount of coarse material supplied locally, probably relating to the lateral incision of the meander loop into local bedrock. Terrace C deposits indicate both the long-distance transport of the coarse assemblage from upstream and the local input of material from along the Rambla del Saltador. Terrace D deposits are dominated by local input of material and they also record the capture event and be-heading of the Aguas/Feos master stream by the loss of the long-distance transport of hornblende schist. Therefore it can be seen that the terrace deposits preserved in the El Saltador sub-reach exhibit sediment provenance characteristics associated with both long-distance transport of the sediment, and with locally supplied sediment sources. Once again the terrace sequence indicates the increasing importance of locally eroded material to the sediment load through time. The loss of Sorbas drainage can be identified in the sediment assemblage and thus the sediment provenance signal generated due to the loss of drainage has to be considered. However, the sediment assemblage indicates the erosion of local bedrock contributes more sediment as the fluvial system incises and decreases its gradient. The coastal portion of the Rio Alias is also complicated by the base-level fluctuations caused by sea-level fluctuations accentuating incision into local bedrock. The sediments preserved indicate both similarities and differences between the coarse and fine sediment assemblage, reflecting both sediment source locations upstream and local incision and liberation of both coarse and fine material.

6.2.4 Process Implications

When the coarse assemblage is analysed via lithological, particle size and shape analysis and the fine sediment assemblage is analysed via petrological thin section/SEM and magnetic analysis fundamental questions regarding process variations can be addressed. Throughout the drainage basin of the Rio Alias the provenance signal generated by the coarse and fine sediment assemblage varies. In some locations the signal generated by both the coarse and fine sediment assemblages indicate the same provenance, whilst in other locations the fine and coarse sediment assemblages indicate different lithological source areas. Tables 6.1 and 6.2 summarise the general sediment provenance variations of the alluvial deposits of the modern Rio Alias and the terrace sequence.

The lithological composition, the degree of cementation and the mechanical strength of the bedrock all influence the grade of the material available for transportation by the fluvial system. In areas where the bedrock units are characterised by sandstone or volcanic rocks, and to a lesser extent the schist of the Alpujarride complex, sediment can be rapidly delivered to the <2mm fraction. The more resistant limestone rocks, meta-carbonates (part of the Alpujarride complex) and some resistant facies assemblages within the sandstone/volcanics/schist, liberate coarse material that is input to the system initially as large clasts only (B axis > 2mm). Consequently it is an oversimplification to assume that the fine sediment assemblage reflects the input of material sourced from significant distances upstream that has been deposited by flood events, and the coarse

Sub-reach	Dominant Source Area	Suspended Load Source	Bed-load Source
Lucainena	*Local*	*Local*	*Local*
Polopos	*Local*	*Local*	*Local*
Argamason	*Local*	*Distant*	*Local*
El Saltador	*Local*	*Local*	*Local*

Table 6.1. Qualitative model of sediment-source ascription for the modern channel.

Sub-reach	Dominant Source Area	Suspended Load Source	Bed-load Source
Lucainena	*A-B: Local/Distant* *C-D: Local/Distant*	*A-B: NA* *C-D: Local/Distant*	*A-B: Local/Distant* *C-D: Local/Distant*
Polopos	*A-B: Distant* *C-D: Distant*	*A-B: Distant* *C-D: Distant/Local*	*A-B: Distant* *C-D: Distant/Local*
Argamason	*A-B: Distant* *C-D: Local*	*A-B: NA* *C-D: Local*	*A-B: Distant/Local* *C-D: Local/Distant*
El Saltador	*A-B: Distant* *C-D: Local*	*A-B: Distant/Local* *C-D: Local*	*A-B: Distant* *C-D: Local/Distant*

Table 6.2. Qualitative model of sediment-source ascription for the terrace sequence.

sediment assemblage is locally derived. Furthermore in the Argamason sub-reach the fine sediment assemblage is clearly generated from local incision into the volcanic bedrock as the signal generated is dominated by the presence of volcanic minerals that cannot be sourced from elsewhere.

The coarse sediment assemblages however, in terraces B and C downstream of the Feos junction indicate long-distance transport of the coarse material by the presence of hornblende schist. The pre-capture terrace sequence of the Rio Alias (terraces A-C) from the Feos junction to the coast generally exhibit long-distance transport of the coarse sediment assemblage, evidenced by the consistent presence of the hornblende schist (sourced in the Sierra de los Filabres). The fine sediment load of terrace C (pre-capture drainage) at the Feos junction also indicates the presence of grains that are sourced in the high-grade metamorphic rocks and therefore indicate long-distance transport of the fine material.

The two examples cited above relate to the terrace sequence. The fine sediment load of the terrace sequence has only been analysed using magnetic analysis. Consequently the provenance patterns indicated need to be treated with caution as the magnetic signal will be dominated by the presence of ferrimagnetic minerals sourced in the volcanic/high-grade metamorphic rocks, even when present in extremely small concentrations. Thus, other minerals may proportionally dominate the assemblage but they will not be recognised in the magnetic signals presented. Petrological/SEM analysis would be needed to accurately determine the sediment provenance characteristics of the fine sediment load of the terrace sequence.

The provenance signal generated on the modern channel indicates the general dominance of local supply of material to the fluvial system for both the coarse and fine sediment loads. The modern channel is the latest phase of evolution of the Rio Alias and in all the sub-reachs the general indication is that of the dominance of locally supplied sediment generation. In the Argamason sub-reach there is an exception to this generalisation where petrological and SEM analysis indicates the dominance of Alpujarride material that is sourced c.6km upstream. Magnetic analysis does not indicate this as the signal is dominated by the presence of the more highly magnetic material derived from the local volcanics.

The general assumption is often made that in fluvial systems the fine sediment assemblage is sourced from significant distances upstream and has been transported long-distances in floods whereas bedload transport is more local and more sporadic. The modern system in operation on the Rio Alias suggests that this is not the case and the majority of the fine sediment deposited in each portion of the system is sourced locally. Perhaps ephemeral flood-dominated systems such as the Rio Alias are characterised by locally derived fine material, especially during incisional regimes.

Overall there is a change in the provenance signals generated by the coarse and fine sediment loads as the fluvial system evolves. This can be related to a change in the transportational processes dominant in the system. In the early history of the fluvial system (particularly terraces A, B and C) a large component of the alluvial sediments are generally sourced from significant distances upstream, suggesting significant proportions of both the fine sediment load transported as suspended sediment and the coarse sediment load, transported as bedload, are both sourced from upstream sources. There are two possible explanations for this; (i) a less dissected landscape does not liberate significant amounts of locally eroded bedrock, and (ii) during terrace stages A-C the Rio Alias downstream of the Feos junction was a larger river system with much greater stream power capable of transporting all sediment greater distances. In many fluvial systems we assume the coarse bedload component is sourced locally, however in the early stages of evolution in the Rio Alias the coarse sediments are sourced both from long-distances upstream and from local incision. Similarly through time the suspended load sediments deposited appear to be sourced from local incision and not from downstream transport of material from significant distances upstream during flood events.
Variations in the provenance signal generated by the coarse and fine sediment loads would be expected due to the difference in transportational processes acting on the different grains/clasts and this is observed within some reaches of the Rio Alias. However the evidence presented here suggests this may not always be the case and we can speculate about the possible reasons for this. Firstly, as the fluvial system develops and incises into the landscape, erosion of local bedrock increases and provides a new *localised* source of sediment to the system. Lithological characteristics then become increasingly important as those rocks that are easily eroded (such as marl and unconsolidated sandstone) will quickly enter the fine sediment fraction and indicate a local sediment source, whilst the more resistant rocks will form large clasts and may only be moved small distances with each flood event. Thirdly, the flood dominated nature of ephemeral systems, where sediment can be deposited rapidly on the waning flood is also conducive to sediment being trapped rapidly after erosion and entrainment, consequently

indicating local sediment provenance. Resistance to erosion of bedrock material and the nature of the sediment that is liberated, the flood dominated nature of the system and the increasing amount of incision through time explain the similarities of the bedload and the suspended indicated on the modern channel within most reaches of the Rio Alias.

The provenance signal generated by both the coarse and fine sediment loads, indicates a progressive change through time in the source area of the sediment delivered to the fluvial system. As the system evolves an increasing local supply of sediment is indicated. It is likely that this is due to the incision of the fluvial system into bedrock introducing locally eroded material, however this signal is somewhat complicated by capture-related provenance variations, such as the loss of hornblende schist. Consequently when analysing provenance variations we must consider both the loss of source areas through be-heading of drainage and, the impact of the changing morphology of the constantly evolving fluvial system.

6.3 Methodological Implications of the Combined Suspended Load/Bedload Approach

6.3.1 Introduction

A combination of petrological thin-section analysis, SEM analysis and magnetic analysis was performed on the <2mm sediments of the modern channel. The combined approach allowed detailed observations of the sediment lithological and mineralogical characteristics to be made. Consequently sediment source areas could be elucidated. The different methods used have varying degrees of success on the modern sediments of the Rio Alias. The petrological/SEM analysis provides semi-quantitative results in terms of the proportions of the grains present and the key minerals associated with the grains, and allowed sediment source ascription to be confidently inferred. Magnetic analysis generally supports the petrological/SEM analysis and, sometimes adds valuable information to the interpretation.

6.3.2 Methodological Sensitivity

Samples from the modern channel at key locations and tributary junctions (as described in Chapter 5) of the fine sediment load (<2mm) were taken, impregnated with resin and cut into standard thin sections. The grains were identified and counted (300 grains a slide). The slides were not of sufficient quality to allow all minerals to be identified (J.

Marshall, University of Liverpool, Pers Comm) however, the lithological characteristics of the grains were easily identified and consequently the bedrock source area could be determined. Grain counts allowed a semi-quantitative approach to sediment source ascription to be made. Direct identification of the grains via the microscope means there is little or no error in attributing a source location as the outcrop locations of each bedrock unit are known. Thus a detailed reconstruction of sediment source ascription is possible. However, the various Neogene basin-fill units may display similar lithological properties. For example the calcareous sandstones may present similar micritic fabric in some facies, as the reef limestone or calcarenite rocks. With standard thin-section analysis (like that employed in the current study) dolomitic limestone cannot be differentiated from standard Calcium Carbonate limestone. This introduces problems when considering the meta-carbonate of the Alpujarride complex. The meta-carbonates cannot be distinguished from basin-fill limestones; consequently all micritic material is identified as one unit. Fortunately the majority of the Alpujarride complex is composed of low-medium grade schists that are easily identified under the microscope. The weakness of the thin-section approach is thus indicated.

The material preserved in the modern channel is dominated by sand-grade material with extremely small amounts of silt and clay material. Consequently the grain counts are overwhelmingly made upon the sand grade material, and as such the silt/clay material is largely ignored (as the material preserved is not of sufficient quality to allow detailed grain identification). However, the silt and clay material is present in such small quantities that further investigation of the sediment properties would not yield useful information regarding sediment source provenance patterns.

In the distal portion of the system where the channel is incising into the same lithological units as it was in the headwater areas, there is no way via grain analysis, of distinguishing if grains are sourced from the more distal or proximal outcrops of the same lithological unit. This introduces some degree of uncertainty to the interpretation of fine sediment being sourced from local incision, if we cannot confidently rule out any upstream sources of the material.

The pitfalls in the analysis of grains in thin-section to establish provenance source areas have been highlighted; however the technique does produce reliable semi-quantitative results in a fairly quick and cheap manner. There is little error when determining the source lithology of the material, though there may be more than one possible source location for the given lithological characteristics.

SEM analysis of the grains allows detailed information to be gathered regarding the mineralogical composition of the lithic grains and consequently the mineralogical assemblages characteristic of each lithological unit can be inferred. The SEM therefore obviously provides important information regarding the mineral assemblage contained in the grains. However, the SEM data are most useful when combined with the data obtained from petrological-thin section analysis, as both the lithic grain and mineral assemblage can be inferred at each site. The SEM allows differentiation of standard carbonate material from dolomitic limestone, and this can be helpful in differentiating material supplied from the meta-carbonate (dolomite) unit of the Alpujarride complex from the standard carbonate grains sourced in the limestone rocks of the Neogene basin-fill. SEM analysis in the Polopos sub-reach allows us to infer that the dominant source of the quartz grains is from the Alpujarride vein quartz and not the local sandstone. This is due to the identification of single quartz grains associated with chlorite and micas, thus indicating the Alpujarride unit as the source whereas the sandstone is characterised by cemented lithic fragments. The combined petrological/SEM analysis therefore increases the degree of accuracy possible for the sediment source ascription of the fine sediment load. In the Argamason and El Saltador sub-reachs SEM identification of volcanic grains allows the contribution of the volcanic rocks to the fine sediment assemblage to be inferred. SEM analysis does identify the compositional differences between dolomite and calcite. Quartz grains derived from sandstones can be differentiated from the grains generated from the metamorphic schists as they are preserved as agglomerate grains whereas the schists are often single poly-crystalline grains. As already noted, the combination of petrological and SEM analysis results in an accurate semi-quantitative assessment of the proportion of each sediment source.

Magnetic analysis generally supports the interpretations made using the data obtained from the petrological/SEM analyses. The basic magnetic analysis performed here if considered on its own, is not of sufficient detail to infer sediment provenance ascriptions for the sediment assemblage (see below). However, when considered along with the petrological/SEM data it provides further support for the provenance source inferred. The magnetic analysis does provide useful information regarding particle-size characteristics and the presence of volcanic/iron-ore minerals that would not otherwise be recognised. Magnetic analysis was performed on a particle-size basis and this provides information regarding the concentration of grains into discreet particle-size fractions. Magnetic signals generated by the sandstone units and the volcanic rocks peak, in particular size fractions; the fine and medium sands. Thus the magnetic signals generated allow us to infer that the sediment generated (through mechanical breakdown of these rocks) is focused into particular particle-size fractions. Consequently this aids in the interpretation of the dominance of locally supplied material to the fine sediment assemblage.

In the Lucainena sub-reach magnetic analysis provides data regarding the presence of ferrimagnetic minerals that must be sourced from the mineralization zone and associated mining spoil heaps. Petrological analysis does not identify these grains, though the presence of Alpujarride schist grains and opaque grains (identified as Fe oxide on the SEM) was noted. Consequently the presence of the grains sourced in the mineralization rocks was only clearly identified by the strong magnetic signal generated in the magnetic analysis. Petrological/SEM analyses overlook the presence of these grains. Magnetic analysis also clearly identifies the presence of volcanic material in the fine sediment assemblage as a strong magnetic signal is generated.

Magnetic analysis is valuable for the identification of mineral assemblages with strong magnetic signals such as the volcanic and mineralization rocks. However the presence of minerals with weak magnetic signatures is largely masked and ignored, as the presence of minerals with strong magnetic properties dominates the magnetic measurements. Parameters such as HIRM go some way to determining the presence of minerals such as haematite and goethite, but minerals such as quartz, calcite and gypsum will not be registered by the magnetic measurements when even extremely small amounts of ferrimagnetic minerals are present. This introduces a significant problem to the interpretation of the magnetic measurements in terms of sediment source ascription as large proportions of the sediment contained within the sample are effectively ignored. Therefore there is a bias introduced to the results and consequently the magnetic analysis does not produce quantitative results, but, can produce reliable provenance indications when used as a marker tool for the bedrock materials. The magnetic analyses performed here were at a fairly basic level (focusing on concentration parameters) in order to assess the applicability of such an approach to questions of sediment provenance ascription in semi-arid ephemeral systems. The magnetic analysis was useful in determining the input of strongly magnetic minerals to the sediment assemblage and also at determining the particle-size range in which grains from particular source rocks were concentrated. Consequently the magnetic analysis was successful in addition to the petrological/SEM analysis, highlighting the presence of minerals that the thin-section analysis had not recognised as significant.

A large proportion the bedrock units feeding the Rio Alias comprise minerals that do not carry high magnetic signals and in the presence of ferrimagnetic material the presence of such minerals is not readily recognised. More detailed magnetic analysis using magnetic grain-size indicators, inter-parametric ratios, bi-variate plots could yield more detailed information regarding the mineral assemblage. However, such analyses were beyond the scope of the current study as a first order attempt at judging the applicability of magnetic analysis. Previous work on magnetic un-mixing models (particularly by Lees, 1990) would indicate that the Alias drainage basin is not suitable for such an approach, as the lithological units do not yield magnetic characteristics that are individually distinct. A magnetic unmixing model approach may however be viable on a sub-reach scale and at specific tributary junctions (such as that of the Rio Alias and the Rambla del Saltador). Magnetic analysis as a first order indication of sediment composition or, as an indication of a strong change in source area provenance (i.e. in identifying capture related changes in source area: e.g. the Aguas/Feos capture-related loss of drainage) is a suitable approach. Furthermore the use of magnetic measurements as a first order attempt to identify capture related changes in fine sediment characteristics is strongly recommended as a cheap and quick methodological approach.

When analysing the fine sediment assemblage in the terrace sequence, magnetic analysis has not been used to amplify petrological and SEM data but it has been used in isolation. Consequently there are questions raised over the sediment assemblage inferred to be present in each terrace unit, as the magnetic analysis does not identify all minerals present. In locations where the magnetic signal is dominated by very magnetic minerals such as those associated with the volcanic rocks in the El Saltador sub-reach, the signal from carbonate, quartz or sandstone is ignored and so the analysis provides no information regarding the presence or absence of these minerals.

The combination of petrological and SEM analysis has been successful in providing a semi-quantitative approximation of the proportion of each lithological grain type contained in the fine sediment assemblage. Though there are short-comings in the approach outlined, the techniques identify the grain assemblages and as such infer sediment source locations. Magnetic analysis further supports, and in two cases, provides extra information regarding the lithological composition of the sediment assemblage. Furthermore information regarding the concentration of particular lithological units into discreet particle-size ranges can be inferred from the magnetic analysis. This allows process-related variations in the provenance of the fine grained material to be ascertained. Consequently variations in the mode of sediment transportation through time can be inferred with implications for the understanding of the evolution of ephemeral rivers.

Chapter 7
Geomorphological Evolution: The Implications

Nickpoint development in a groundwater calcrete at the Rambla Honda/Rio Alias confluence

Chapter 7
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7.1 Introduction

The fundamental controls of the evolution of fluvial systems are tectonics, climate and base-level. Climate influences the supply of water and sediment to the fluvial system and consequently controls the critical stream power relationships (Bull, 1979), therefore driving aggradation and incision within the fluvial system. Tectonics may indirectly influence the delivery of sediment to the system by increasing erosion rates due to pronounced uplift of sediment source areas. Most importantly tectonic activity may also directly affect the fluvial system by altering local base levels and stream gradients, which in turn alters the critical power relationships. Base-level variation, via sea-level change or tectonic activity, alters critical stream power relationships by altering stream gradient. Within the context of the drainage basin, river-capture may lead to drainage reorganisation and thus influences the evolution of the fluvial system by re-routing water and sediment between drainage and/or sedimentary basins. The underlying geology indirectly impacts the evolution of the fluvial system due to variations in lithological resistance and the resulting delivery of sediment to the system.

The interaction between tectonics, climate, base-level change and river-capture on the Rio Alias varied between the 4 sub-reaches over the timescales of the Quaternary. Climate variation is controlled by global glacial/interglacial cycles, in this area, with alluvial aggradation coincident with glacial phases and dissection with interglacial phases. Tectonism influences the evolution of the Rio Alias indirectly by regional epeirogenic uplift and directly by altering local base level and stream gradients due to deformation along individual fault structures. Base-level changes due to Quaternary sea-level fluctuation are inherently driven by climate variation (i.e. glacial/interglacial cycles). The evolution of the Rio Alias is also significantly impacted by a regional river-capture event that led to decreased stream power along the Rio Alias below the Rambla de los Feos confluence. The impact of interacting climate, tectonic and base-level controls on the evolution of the Rio Alias is discussed below.

7.2 The Sequence

7.2.1 Introduction

Recent developments in Uranium/Thorium (U/Th) dating of pedogenic calcretes has allowed an increasingly reliable chronology to be developed in arid/semi-arid environments. This is true in southeast Spain (e.g. Candy et al., 2004; 2005). The establishment of a reliable absolute chronology in the drainage basin of the Rio Alias has not been possible as part of the current study, however a detailed program of field work has allowed the terrace sequence of the Rio Alias to be confidently correlated with that of the Rio Aguas in the Sorbas basin, were landforms have undergone more detailed chronological analysis. Relative chronologies on the Rio Alias sequence were established by field mapping of the terrace record and both field and laboratory analysis of soils including magnetic analysis and correlate with the Sorbas basin sequence. Recent OSL dating further supports the correlation between the terrace units of the two areas.

7.2.2 Absolute Chronology

Absolute dating of the terrace sequence of the Rio Alias was beyond the remit of the current study, however an attempt has been made to date fluvial terrace sediments by Optically Stimulated Luminescence (OSL). Two samples were taken from terrace C and D on the Rio Alias below the tributary junction of the Rio Alias and the Rambla de los Feos, in order to constrain the timing of the Aguas capture event. Terrace C deposits could not be dated due to unforeseen problems with the material sampled (B. Mauz (University of Liverpool), Personal Communication; Appendix 2). However terrace D has been dated to 32.5 ± 3.4 ka (See Appendix 2 for OSL data) comparable with the dates obtained by Candy et al. (2005), c.30.3 ka, for terrace D1 on the Rio Aguas in the Sorbas basin. The terrace D deposits dated in the Sorbas basin have been complicated by local ongoing tectonic activity during terrace D times and the fluvial system consequently developed in several phases, hence the terminology D1 reflects the initial terrace deposits that pre-date the deformation phase. The similarity in the absolute dates supports the field based analysis indicating compatibility between the D terrace sequence in the Sorbas basin and along the Rio Alias. Field mapping established continuity along the Rio Aguas and the Rio Alias for terrace levels A-C. Consequently, dating of the other terrace units in the Sorbas basin (Kelly et al., 2004, 2005) can be used to infer ages of the terrace units on the Rio Alias.

Field based correlation of the terrace units along the Rio Alias, and between the Rio Alias and the Rio Aguas, was presented in Chapter 4. The absolute chronology of the terrace deposits has been established for the Rio Aguas in the Sorbas basin by Candy et al. (2004; 2005). The oldest terrace stages A and B have not been constrained with great precision, but the terrace A surface is inferred to be at least 304ka old, and is likely to be older, perhaps up to c.400ka (Candy et al., 2005). The aggradation of terrace A therefore predates that. The surface associated with terrace B is inferred to date from c.207ka (Candy et al., 2005). Both dates obtained from U/Th dating of pedogenic calcretes are not precise, due to the nature of the material dated and limitations of the technology at the present time. However the dates obtained by Candy et al. (2004) provide some chronological control on the early terrace stages.

Terrace stage C has been constrained more precisely (Candy et al., 2005). The aggradation of terrace C deposits occurred prior to c.78 ka and the terrace surface was abandoned prior to c.70ka following the capture event. Terrace D in the Sorbas basin was subject to ongoing tectonic deformation and consequently the terrace has been sub-divided (Mather et al., 2001). However the onset of terrace aggradation (prior to tectonic activity) has been dated to c.30.3ka (Candy et al., 2004), similar to the OSL date for terrace D on the Rio Alias (see above). Stage D evolution terminated in the early Holocene (Candy et al., 2004) with phase D3 (Harvey et al., 1995; Mather et al., 1995).

The chronology of the terrace sequence preserved along the Rio Aguas indicates that the aggradational phases of the later terrace stages correlate well with global glacial phases; terrace stage C of the Sorbas basin coinciding with the beginning of the last glacial phase (Oxygen Isotope Stage (OIS) 4) and terrace D1 of the Sorbas and Almeria basins corresponds with the beginning of the last glacial maximum (LGM: OIS 2). Correlation of the early terrace stages (A and B) with particular phases of global cooling is not possible, but a generalisation may be made inferring terrace A aggradation as likely to relate to OIS12 and terrace B to OIS 8. This is similar to the late-Quaternary alluvial fan sequences recorded across the region. In Cabo de Gata (Harvey et al., 1999) and Tabernas (Harvey et al., 2003) aggradational phases broadly correlate with glacial phases and dissection with interglacials (Macklin et al., 2002; Fuller et al., 1998).

7.2.3 Soil Magnetic Properties

As discussed in Chapter 4 soil preservation is extremely poor on the terrace sequence of the Rio Alias. Magnetic analysis of the soils on the terraces of the Sorbas basin (Harvey

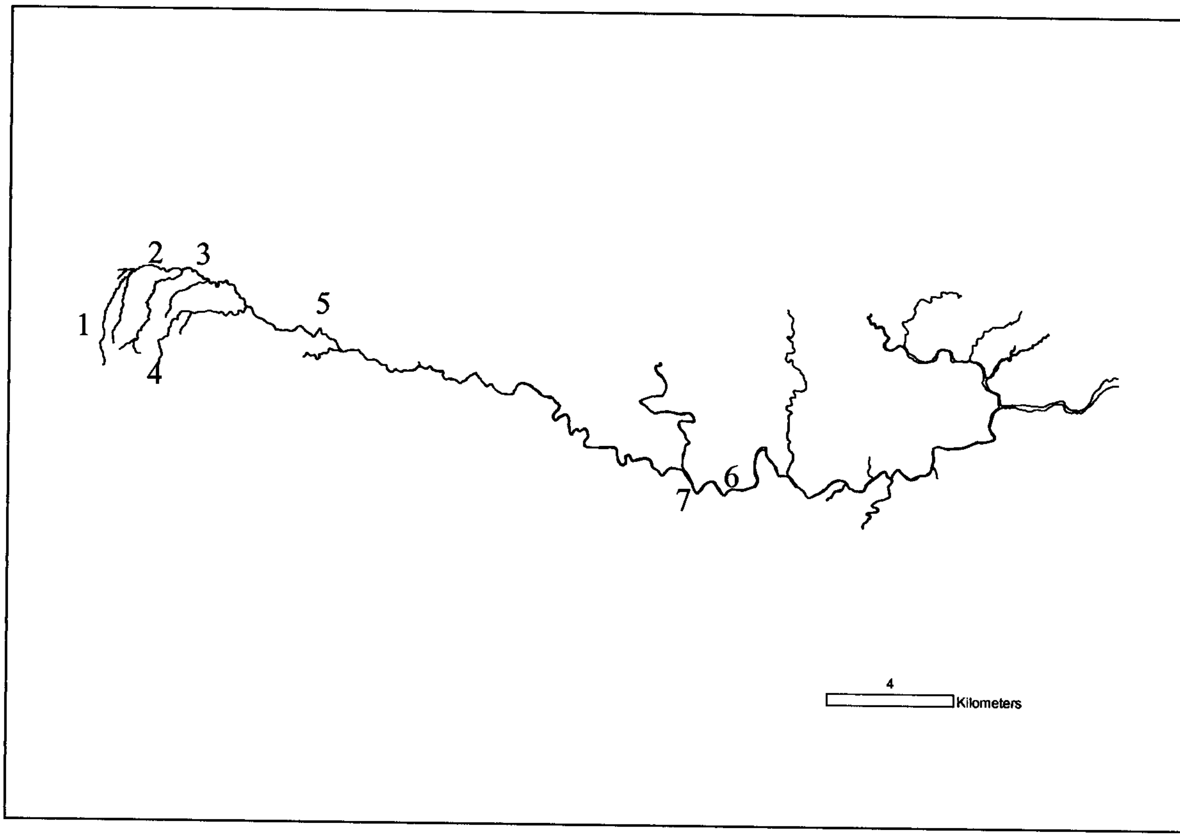

Figure 7.1.Location of soils samples taken for magnetic analysis on the Rio Alias. For sample key see table below.

Sample and Sub-reach	χ_{LF} (10^{-8} m^3 kg^{-1})	χ_{FD} %	**SIRM** ($10^{-5}Am^2 kg^{-1}$)
1. Terrace A- Lucainena	190.74	10.33	2563.66
2. Terrace A- Lucainena	203.99	7.60	2745.35
3. Terrace B- Lucainena	624.84	6.971	10379.94
4. Terrace C- Lucainena	133.44	9.52	1777.65
5. Terrace D- Lucainena	52.10	8.81	766.66
6. Terrace C- Polopos	282.96	10.56	4039.07
7. Terrace D- Polopos	74.65	10.49	797.44

Table 7.1. Magnetic properties of preserved B horizon soils on the terraces of the Rio Alias. For sample locations see Figure 7.1.

et al., 1995; Hannam et al., in prep) has previously been used to establish a relative terrace chronology in combination with analysis of the field-based properties of the soil horizon and calcrete development. Preservation is so limited in the Alias drainage basin that only 7 soil sites were sampled from across the drainage basin (due to access and preservation) and most were located in the Lucainena sub-reach (Table 7.1 and Figure 7.1). Where soils were preserved the B horizon was sampled for magnetic analysis. The magnetic analysis does indicate a general increase in the concentration of magnetic minerals in those soils associated with the older terrace surfaces. Increased χ_{LF} and SIRM indicate an increase in the concentration of magnetic minerals, and χ_{FD} indicates the presence of super-paramagnetic grains associated with pedogenic soil development (Dearing et al., 1985). In contrast with soils of the Sorbas basin, the neighbouring Tabernas basin and alluvial fan soils in the Cabo de Gata volcanic range (Harvey et al., 1995; 1999; 2003; Hannam et al., in prep) $\chi_{FD\%}$ does not appear to show a clear relationship with increasing soil age. This may be related to the degraded nature of the preserved soils, and to the small number of samples preserved, most of which are in the Lucainena sub-reach. The $\chi_{FD\%}$ values are all relatively high, especially for the younger soils when compared with other work from across the region (Harvey et al., 1995; 1999; 2003). It is possible that the anomalous values relate to the presence of extremely magnetic minerals derived from the zone of iron mineralization. In general the magnetic concentration parameters do appear to indicate an increasing magnetic signal with increasing soil age. Unfortunately the number of samples is so small that statistical analysis cannot be performed. Therefore in this case the magnetic properties of preserved soil profiles cannot be reliably used as a corollary to field analysis for terrace correlation. However further detailed magnetic analysis of the soils preserved (such as those used by Hannam et al., in prep) could yield a more reliable indication of soil chronology.

7.3 Controls Upon Fluvial System Evolution

7.3.1 Introduction

The Rio Alias has evolved as a series of almost independent sub-systems that can be thought of as structurally controlled sub-reachs; as defined in Chapter 4. Consequently the relative impacts of tectonics, base-level change and river-capture are different in each sub-reach whilst climatically generated signals are consistent across the region. Therefore the impact of changes in the fluvial system due to tectonics, base-level and river-capture must also be considered at the sub-reach scale.

7.3.2 The Lucainena Sub-reach

The Lucainena sub-reach is located on the southern margin of the Sorbas basin and is defined at its eastern limit by the northern boundary fault associated with the Sierra Alhamilla. The Lucainena system developed as an aggressive, headwards eroding stream during the Plio-Pleistocene (Mather, 1991, 1993a) capturing and diverting Sorbas basinal drainage into the Almeria basin. During the late-Quaternary the Lucainena sub-system has continued to expand its drainage area at the expense of the Aguas system in the Sorbas basin via continued headwards erosion.

Sub-reach base-level control is by the northern boundary fault and the transverse canyon reach. The dominant control on fluvial system development in the Lucainena sub-reach is climate. The sequence of aggradation and dissection represented by terraces A-D primarily reflects the climatic signal. These terraces can be recognised consistently through the sub-reach and are convergent towards the canyon reach (i.e. the incisional levels of terraces B and C become closer to the modern channel towards the canyon reach). The regional climatically generated signal is modified by a small intra-basinal river-capture event (Figure 7.2) and by limited tectonic activity. The river-capture event is within the Lucainena basin and does not divert water/sediment away from the sub-reach, but rather leads to the development of a new tributary system re-routing water and sediment only within the sub-reach. The tributary developed parallel to the mountain front at the village of Lucainena and beheaded part of the drainage previously associated with the Rambla del Penoncillo. The drainage diversion occurred following the aggradation of terrace B and prior to the aggradation of terrace C (Figure 7.2). It is inferred that the aggressive development of the Lucainena village tributary followed a local tectonically driven base-level fall in the area of Los Banos (see Chapter 4 for location) along the Infierno Marchalico Lineament (IML) of Mather and Westhead (1993). The area affected by the loss of drainage initially suggests a loss in stream power reflected in the nature of the alluvial material; i.e. a decrease in the particle size of the material. However the material the stream was incising into at this time is fine-grained sandstone, and as such the particle size of the alluvial material is likely to be fine-grained, regardless of the power of the fluvial system. The newly developed Lucainena village tributary, rapidly cut a wide valley due to the aggressive development of the tributary within the easily eroded Tortonian sandstones and marls.

There is also limited evidence on the northern margin of the Almeria basin along the Rambla de los Feos to suggest the continued uplift of the Sierra Alhamilla/Cabrera during

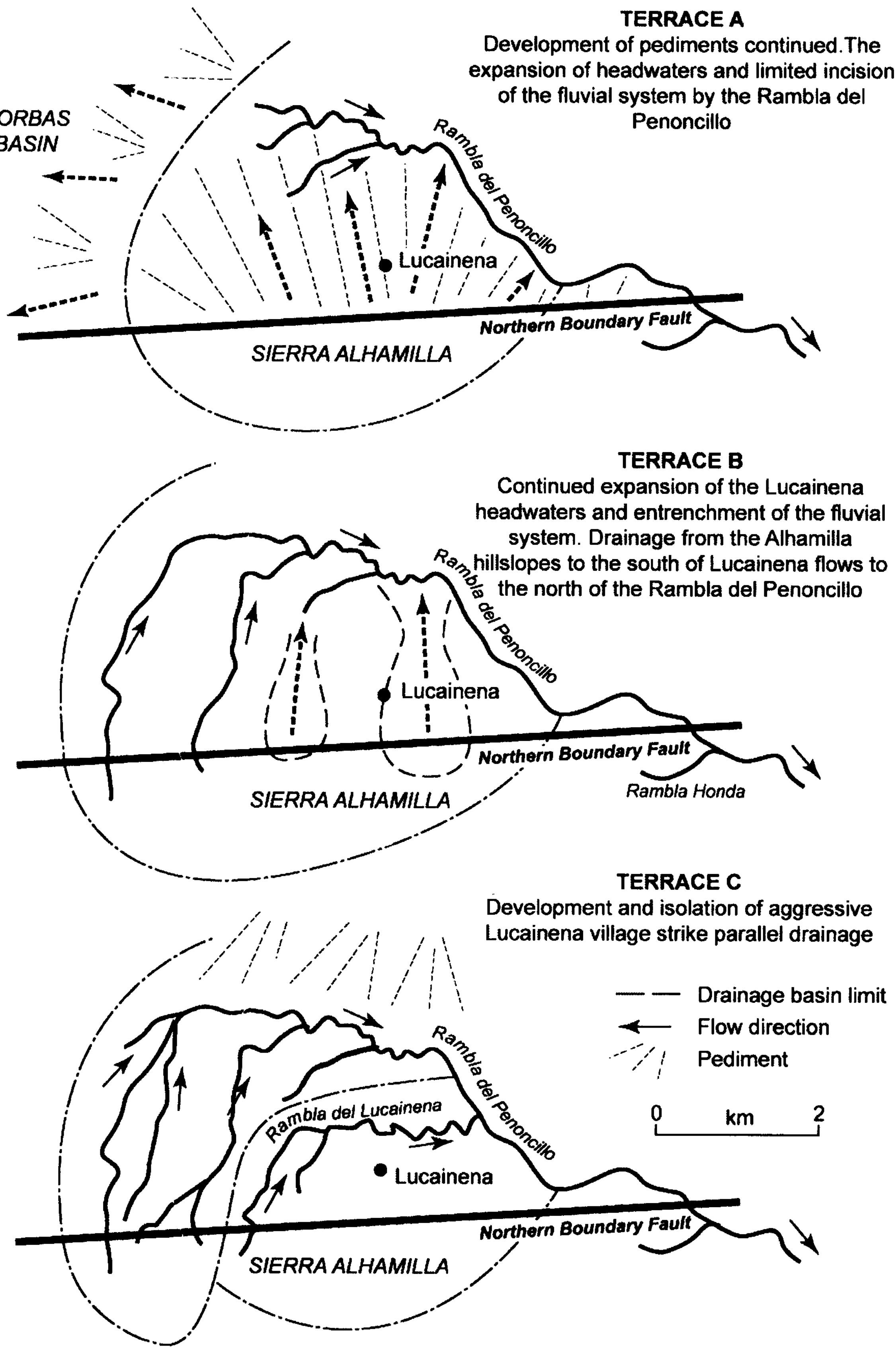

Figure 7.2. Evolution of the Lucainena sub-reach, related to river-capture related re-organisation of drainage.

the latter half of the Quaternary (Harvey and Wells, 1987). In the Lucainena sub-reach terrace A is characterised by a tilted surface suggesting possible tectonic uplift of the Sierra Alhamilla, however there is not sufficient preservation of the alluvial sediments to observe tilting of bedding planes. The incisional base of terrace B and terrace C, converge towards the transverse reach of the headwaters indicating limited uplift of the Sierra Alhamilla during the incisional phases. There is no evidence of tectonic deformation of the alluvial sediments. Therefore tectonic activity appears to modify the development of the fluvial system in two ways; river-capture driven by base-level lowering due to normal fault movement and the limited raising of base-level via epeirogenic uplift of the Sierra Alhamilla.

Tectonic activity does not significantly alter the climatically generated signal in the Lucainena sub-reach. Phases of terrace aggradation and incision appear to accord with the regional picture, and therefore are driven by northern European glacial cycles. There is no tectonic modification of the overall aggradational/incisional cycle as demonstrated elsewhere in the Rio Alias drainage basin (see below). The impact of local tectonic activity has been to alter base-level and consequently drive local drainage re-organisation. The change in base-level has driven the development of the Lucainena village tributary system and therefore some degree of incision, however the overall terrace sequence relates to the regional climate signal.

7.3.3 The Polopos Sub-reach

The Polopos sub-reach is located on the southern margin of the Sierra Alhamilla defined to the west by the southern boundary faults in the area of Polopos village and to the east by a nickpoint; the position of which is structurally defined by an anticline developed in Pliocene Cuevas Viejas marine sandstones. Above the confluence of the Rambla de los Feos and the Rio Alias there is little direct evidence of tectonic modification of the fluvial system. Initially the system developed as an alluvial fan as the Rio Alias exited the transverse canyon reach and its associated confinement. On the southern margin of the Sierra Alhamila on the Rambla de los Feos terrace B (of Harvey and Wells, 1987) exhibits post-depositional normal faulting. Furthermore, Harvey (2005) suggests that tortuous incised meanders indicate accelerated incision due to gradient increase. Such incised meanders, indicating cut offs, are well developed south of Polopos and may indicate tectonically induced increases in gradient south of the Sierra Alhamilla. However the tectonic activity does not override the climatically generated signal.

Below the Alias/Feos confluence there is evidence of post-depositional faulting of terrace A fluvial sediments, but no evidence of tectonic activity exhibiting control over the evolution of the fluvial system (i.e. lateral incision of the channel, syn-sedimentary deformation of the fluvial deposits etc). There is no evidence of tectonic activity disturbing terrace B deposits apart from that on the Rambla de los Feos but preservation of terrace B deposits is limited across the sub-reach. In the early evolution of the terrace sequence it can be inferred the dominant control on the fluvial system is climate, with no clear evidence of tectonic modification of base-level beyond accelerated incision away from the Alhamilla mountain front.

Following the aggradation of terrace C however, the capture of the Aguas/Feos system beheaded the Rio Alias of c.70% of its original drainage area (Mather, 2001a). The impact of the loss of drainage area varies spatially across the sub-reach. In the upper Feos valley upstream of the Sierra Alhamilla alluvial fans prograded across the valley; the Rambla de los Feos was no longer capable of incision due to the loss of drainage area and the consequent decrease in stream power (Harvey and Wells, 1987). In the lower Feos valley, downstream of the Sierra Alhamilla transverse reach, stream power was sufficient for incision to ensue, though incision was reduced following the capture event. On the Rio Alias below the Feos confluence, the loss of Sorbas drainage is reflected in the decrease in size of bedform geometry, a change in sediment provenance characteristics and a change in alluvial style from channelised flow to sheetflow deposits (Maher et al., in press). The climate signal is greatly modified in the Polopos sub-reach after the beheading of the Aguas/Feos master drainage following the aggradation of terrace C. Consequently the phases of aggradation and incision on the Rio Alias in the Polopos sub-reach reflect climate variation, but the alluvial style, sediment provenance characteristics and degree of incision reflect the loss of drainage due to river-capture. There is limited evidence of syn-depositional tectonic activity within terrace C deposits downstream of the Alias/Feos junction, however the degraded quality of the outcrop does not allow any clear inferences to be made though all other evidence points to little or no modification of the fluvial system due to tectonic activity..

The eastern portion of the Polopos sub-reach is adjacent to the western limit of the Argamason sub-reach; the boundary between the two sub-reachs is defined by the structurally controlled nickpoint developed in the Cuevas Viejas sandstone. The tectonic base-level lowering in the Argamason sub-reach (to be discussed in detail below) caused incision throughout the Argamason sub-reach. There is no evidence however, of the incision wave caused by the tectonic base-level lowering extending upstream of the nickpoint and into the Polopos sub-reach.

7.3.4 The Argamason Sub-reach

The Argamason sub-reach is defined to the west by the modern nickpoint west of Argamason and to the east by the nickpoint developed near to the village of Llano don Antonio (see Chapter 4). The Rio Alias crosses the Carboneras Fault Zone in the Argamason sub-reach and the Quaternary evolution of the fluvial system has been greatly modified by tectonic activity along the fault zone and subsidiary faults. It has previously been established (e.g. Harvey, 1990; Candy et al., 2004; 2005) that the regional patterns of Quaternary aggradation/incision are related to northern European glacial/inter-glacial cycles. The A-D terrace sequence has been significantly modified by tectonic activity in the Argamason sub-reach. In the sub-reach terrace stage C has been sub-divided into stages C1 and C2. Tectonic base-level lowering downstream of Argamason village caused lateral incision of the channel belt and the development of tortuous meanders as the channel increased its length to compensate for the increased gradient. Furthermore terrace C2 and D deposits exhibit syn-depositional and post-depositional deformation. Following stage C1 the channel cut-off the meander loops as the base-level fall continued.

The climatically generated signal has been modified due to normal fault activity along the Carboneras fault and subsidiary fault lines. The tectonic activity has altered both the geomorphological and sedimentological properties of the C1-D terrace sequence upstream of the zone of base-level change. Terrace level C2 was created solely by tectonic activity. Downstream of the zone of tectonic activity base-level lowering altered the level of incision of the channel; the incisional level of terrace C is lower than that of the modern channel. The amount of incision is not proportional to the climate-driven incisional signal, but is a function of tectonic base-level lowering.

Tectonic activity lowered the local base-level of the fluvial system, an incision wave was generated and transmitted upstream. The incision wave was held up by the development of a nickpoint 3-4km upstream, itself positioned and spatially restricted by a post-Pliocene anticline structure. The nickpoint developed during terrace stage C2 and is associated with the tectonic base-level lowering, not with climatically generated variations in aggradation and incision. There is little preservation of the early terrace record through the Argamason sub-reach, however it can be inferred that the climatically generated sequence from terrace C (c.78ka: Candy et al., 2004) to modern times has been considerably modified by local tectonic activity.

7.3.5 The El Saltador Sub-reach

The El Saltaldor sub-reach is located at the seaward end of the Rio Alias and as such has been subject to large variations in base-level due to Quaternary sea-level fluctuations. Preservation of terrace deposits is limited in the El Saltador sub-reach and a detailed reconstruction for the sub-reach is not possible. However, the remaining terrace units do allow a general palaeoenvironmental reconstruction to be determined. Little is known about the early evolution of the fluvial system (terrace A) as there is only one terrace remnant preserved. Terrace B however, exhibits a complicated pattern of evolution reflecting the combined climatic and eustatic impact on the fluvial system.

At the coast there are two distinct remnants of Quaternary high sea-levels, preserved as raised beach deposits at 30m and 5m above modern sea-level (Figure 7.1). Conventionally these would be assigned to the (now outdated) Tyrhennian I and II stages respectively. The upper unit at 30m has not been dated, however along the coast in the Almeria region and elsewhere in southeast Spain, marine deposits found at this level are thought to be older than (OIS) 7 (Zazo et al., 2003) and thought likely to date to OIS 9. Conventionally this would be referred to as Tyrhennian I, relating to the penultimate major (pre-Riss) interglacial (using the now outdated terminology; Thurber and Stearns, 1965; Dumas, 1977). The lower raised beach deposit is preserved at 5m above modern sea-level. The deposit has not been dated in this area, however it almost certainly relates to OIS 5, as equivalent deposits along the Almeria coast and throughout southeast Spain (Thurber and Stearns, 1965) have consistently been dated to OIS 5 (Zazo, et al., 1981; 2003). Conventionally this would be referred to as Tyrhennian II, dating from the last interglacial highstand (Riss-Wurm: Thurber and Stearns, 1965).

The climatically driven incision prior to terrace B is likely to have occurred simultaneously with a sea-level highstand associated with OIS 9(?), according to the estimated age of terrace B provided by Candy et al. (2004) of c.200ka (i.e. OIS 8 or Reiss in old terminology) . High eustatic sea-level was consequently fore-shortening the base-level of the fluvial system- somewhat similar to the current inter-glacial setting, and this would have limited the amount of incision in the coastal zone. At the seaward end of the sub-reach the incisional level at the base of terrace B exhibits an extremely steep gradient (Figure 7.1) from c.30m above the modern channel to below the level of the modern channel. It is inferred that the steep gradient developed at the base of the terrace B

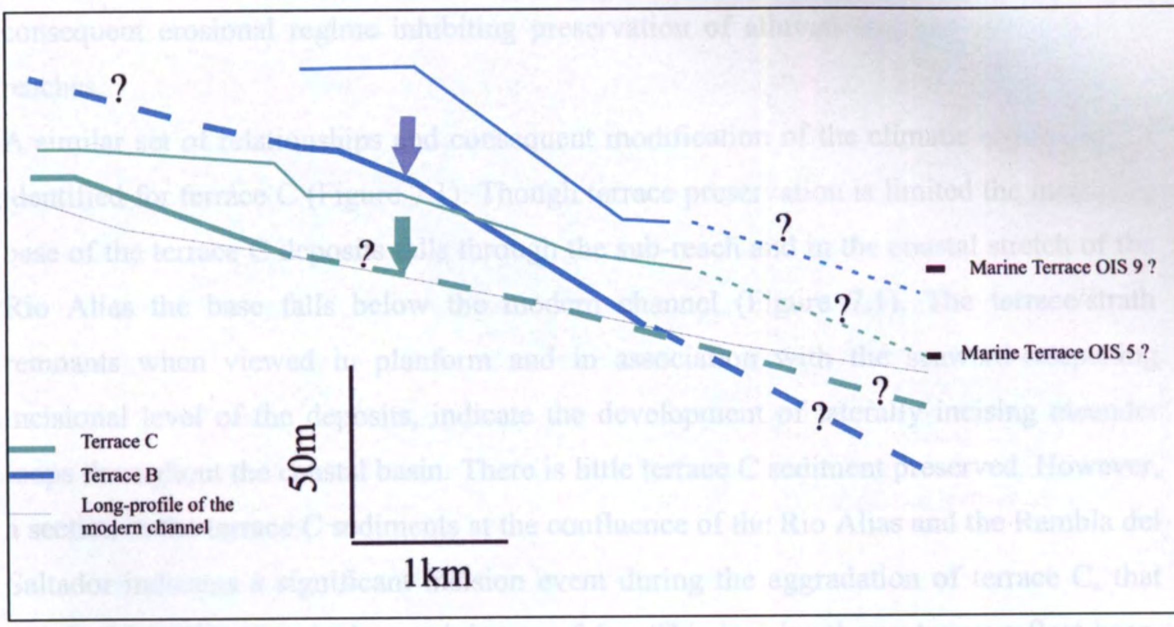

Figure 7.1. The figure indicates the relationship between levels of terrace aggradation/incision and the preserved marine deposits. The incisional base of terraces B and C is indicated by the heavy line (and the arrows) and the level of aggradation by the thin line. Solid line indicates actual level observed in the field, dashed line indicates inferred level of incision/aggradation. Question marks indicate unknown levels.

deposits, is related to the fall in sea-level during the onset of the glacial phase following OIS 9 (?). The falling sea-level would have lowered the base-level to which at least initially the fluvial system was grading and consequently driven a phase of incision that would have overcome the climatically generated phase of aggradation. Terrace aggradation then ensued, burying the incisional surface (Figure 7.1) with a thick accumulation of fluvial sands and gravels. It is thought the development of tortuous meander loops in the coastal portion of the system during terrace B aggradation, relates to the need to increase river length in order to compensate for base-level lowering due to the falling sea-level.

The loose chronological control on terrace B means that the terrace may span more than one glacial/interglacial cycle and consequently the fluvial system may have experienced several phases of sea-level regression and transgression. Preservation is limited in the sub-reach and the terrace deposits preserve only one phase of incision and aggradation. The lack of sediment preservation in the El Saltador sub-reach is likely to be related to the development of steep incisional gradients during sea-level regressions, and the consequent erosional regime inhibiting preservation of alluvial material in the coastal reaches.

A similar set of relationships and consequent modification of the climatic signal can be identified for terrace C (Figure 7.1). Though terrace preservation is limited the incisional base of the terrace C deposits falls through the sub-reach and in the coastal stretch of the Rio Alias the base falls below the modern channel (Figure 7.1). The terrace/strath remnants when viewed in planform and in association with the seaward-steepening incisional level of the deposits, indicate the development of laterally incising meander loops throughout the coastal basin. There is little terrace C sediment preserved. However, a section in the terrace C sediments at the confluence of the Rio Alias and the Rambla del Saltador indicates a significant incision event during the aggradation of terrace C, that trenched into the deposits by a minimum of 6m. This incisional event may reflect base-level lowering due to sea-level fluctuation during OIS 4. The evolution of the fluvial system over the last 30ka is poorly constrained due to the lack of preservation of terrace D deposits.

Due to the lack of terrace sediment preservation in the El-Saltador sub-reach it is difficult to interpret the relative importance of the various controls on fluvial system evolution. There is however, no evidence of tectonic deformation of the sediments and consequently the primary controls of evolution appear to be variations in both climate and sea level. Regional patterns of aggradation appear to be associated with northern hemisphere glacial phases, but in the El Saltador sub-reach eustatic lowering of base-level initially overrides the increase in sediment delivery and the fluvial system incised. The interaction between climate and base-level variations in the sub-reach led to significant modification of the fluvial system. Incision ensued when climate deterioration produced a wave of sediment generation from the hillslopes that elsewhere across the region led to alluvial aggradation.

A regional climatic signal can be identified throughout the Rio Alias drainage basin but the interaction with other factors such as tectonism, river-capture and eustasy varies between the sub-reachs. In the Lucainena sub-reach climate provides the main control on fluvial development with some limited modification by both regional and local tectonic activity and local river-capture. The climatic signal is also dominant in the Polopos sub-reach with minor tectonic modification of the river system and major modification due to river-capture related loss of drainage. The evolution of the Argamason sub-reach also records the dominant regional climatic signal, but, local tectonic lowering of base-level overrides the climate generated phase of aggradation and introduces a localised phase of incision not related to climate variation. The El Saltador sub-reach is similar to the Argamason sub-reach as the climate signal is clearly the dominant driver of aggradation and incision over the late Quaternary. However, sea-level variation appears to have locally altered the terrace sequence with phases of aggradation/incision following base-level variation due to sea-level regression as well as climate fluctuation.

Overall the climate generated signal is most clear where base-level shows the least change and the most stability through the late Quaternary evolution of the Rio Alias. Where base-level change due to tectonism and eustasy has been of a sufficient magnitude to modify the relevant stage of fluvial evolution, the dominant mode of change is associated with local incision.

The incision waves created by the base-level fall associated with tectonism in the Argamason sub-reach and sea-level fall in the El Saltador sub-reach, have been limited in their upstream extent propagating no more than 7km upstream. This is somewhat less than the propagation of tectonically driven incision waves in the neighbouring Tabernas (sedimentary) basin (Harvey, 2002b), and the eastern Alpujarras (Garcia et al., 2003).

7.3.6 Fluvial System Evolution

The climatically generated signal is complicated throughout the drainage basin of the Rio Alias by tectonic lowering of base-level, river-capture and sea-level variations. Consequently a detailed program of field analysis was necessary to identify the late Quaternary terrace sequence, and resolve any modification of the climate signal in the terrace record due to either tectonic base-level/sea-level lowering or river-capture events. Furthermore analysis of sediment provenance indicators (i.e. clast lithology and petrology/mineralogy of the fine sediment load) helped to provide a detailed reconstruction of patterns of provenance variation through time. Analysis of the provenance characteristics of the fluvial sediments provides information regarding both the spatial variation of source rocks, and, changes through time related to river-capture and the progressive development of the landscape (i.e. the developing geomorphology).

The impact of tectonism, river-capture and sea-level change on the evolution of the Rio Alias over time has been assessed. However, in order to fully understand the development of the Rio Alias, we must not only consider changes in the external controls of the fluvial system, but changes that also occur due to the continued, progressive development of the fluvial system itself. Sediment provenance analysis identifies a shift in the source of both the coarse and fine material supplied to the channel with increased incision into bedrock. The incision led to a decrease in downstream gradient of the fluvial system over time, but increasing local relief above the valley. This led to changes in the relative importance of locally supplied sediment in relation to long-distance transportation with progressive incision of the fluvial system. The switch in dominance from distant to local sources of alluvial material is not due to any external variation in climate or base-level, but rather to the continued dissection of the landscape and the associated lowering of the gradient of the fluvial system. Interestingly the fluvial system gets more youthful over time, i.e. the long-term internal coupling/connectivity of the system weakens through time (Harvey, 2002; Hooke, 2003).

The development of the fluvial system is controlled by variations in climate, tectonism, river-capture and eustatic sea-level variations. Changes in sediment provenance reflect these external controls, but also reflect the progressive development and maturity of the fluvial system.

Chapter 8
Conclusions

The Feos Valley and the Sierra Alhamilla

Chapter 8
Conclusions

A combination of both field and laboratory based analysis of the alluvial landforms and sediments of the Rio Alias has elucidated a good understanding of the controls upon fluvial evolution during the latter half of the Quaternary. Inferences can be made regarding the relative importance of climate, tectonics and sea-level changes, and how this relationship varies spatially during the evolution of the river system. Furthermore, analysis of the mineralogical/lithological assemblage of the alluvial deposits allows detailed reconstruction of drainage diversion/beheading, and, a more detailed understanding of the long-term development of incising fluvial systems to be ascertained. The main findings of the current study were:

1. In tectonically active and/or semi-arid environments sub-division of the drainage basin into sub-reaches is vital in order to fully understand the differential evolution of each portion of the fluvial system.
2. The impact of tectonic and sea-level (base-level) variations and drainage re-organisation differs in importance between the sub-reachs, therefore modification of the regionally dominant climatic signal is differential across the Rio Alias.
3. Detailed field analysis of the landforms and alluvial sediments is vital to identify any changes in the climatically generated aggradational/incisional sequence along the Rio Alias due to deformation, base-level lowering or drainage re-organisation.
4. Geomorphological/geological mapping, sediment provenance analysis and field based soil/pedogenic carbonate analysis allows the terrace sequence of the Rio Alias to be matched with that of the master Aguas/Feos system of Harvey and Wells (1987). Consequently a reliable chronological framework can be inferred following the work of Candy et al. (2004; 2005).
5. Tectonic structures including mountain belts, fault lines and folds de-limit sub-reachs and as such are important when assessing the spatial impact of base-level lowering events.
6. Four sub-reachs were defined for the Rio Alias, each sub-reach evolved independently with tectonics, river-capture and sea-level variation impacting upon each part of the system (dependant on location). The sub-reachs:

a. The Lucainena sub-reach: developed largely under the influence of climatic variation with small scale modification of the fluvial system by drainage re-organisation and epeirogenic uplift.
b. The Polopos sub-reach: evolved largely under the influence of climatically generated variations in incision and aggradation with major modification of the fluvial system due to drainage re-organisation between sedimentary basins.
c. The Argamason sub-reach: climate related phases of incision/aggradation were significantly modified in the last 70ka due to local tectonically induced base-level lowering.
d. The El Saltador sub-reach: climatic phases of aggradation and incision have been altered and overridden by base-level variations usually from Quaternary sea-level change.

7. Climate, tectonics eustasy and drainage re-organisation combine to drive fluvial system behaviour during the Quaternary evolution of the Rio Alias. Regionally significant climatically driven phases of aggradation/incision have been significantly modified and overridden by fluvial system activity related to base-level change and river-capture.
8. River-capture and consequent diversion of headwater drainage has led to significant modification of the Rio Alias downstream of the Feos junction. Bedform geometry, maximum clast size and the incisional power (reflected in the incisional base of the terrace deposits) of the river was greatly reduced following the loss of drainage area.
9. Sediment provenance analysis of the terrace sequence provides information regarding the progressive change in the dominant source of sediment as the fluvial system evolves. Early in the evolution of the Rio Alias long-travelled sediment characterised the sediment assemblage to a large extent. However as the system evolved and incision continued, locally supplied sediment came to dominate the alluvial sediment assemblage.
10. The lithological characteristic of the bedrock material also controls the abundance and presence of each lithological clast/grain in the sediment assemblage.
11. Combined SEM and petrological analysis successfully identified, and produced a semi-quantiative estimate of the proportion of each lithological grain type. However the method employed in the current study, and the distinct lack of silt

and clay material, made it to difficult to securely identify the lithological properties of the silt/clay fraction.

12. Magnetic analysis identifies mineral assemblages that form a minor component of the fine sediment assemblage that petrological/SEM analysis failed to identify. However, minerals with a strong magnetic signal also dominate the magnetic assemblage and magnetically weaker minerals are consequently ignored- even if proportionally speaking they dominate the sediment assemblage.
13. Magnetic analysis performed on the terrace sequence identifies the dominant magnetic minerals, but is likely to ignore the paramagnetic/diamagnetic (quartz, calcium carbonate, gypsum etc) contribution which in many cases is likely to be the dominant contibutor. However, no petrology or SEM analyses were undertaken for the terrace record due to time constraints, and as such a detailed reconstruction of sediment provenance ascription is not possible. A more detailed program of magnetic analysis (i.e. Bi-variate analysis, SIMPLEX Linear Modelling) may be successful in producing a more quantitative model, but this is beyond the remit of the current study, would take a significant amount of time and would have to be done on a reach-by-reach approach owing to the size and lithological variation of the Alias drainage basin.
14. Magnetic analysis is therefore best used as a corollary to petrological and SEM analysis and as a first order proxy of mineral composition and consequent identification of provenance variations (i.e. river-capture related drainage be-heading).
15. Clast lithological and grain mineralogical analysis indicates the suspended and bed load components of the alluvial sediments of the Rio Alias (both the modern channel and the terrace sequence) generally indicate the same lithological properties and therefore sediment-source areas. This is likely to relate to the flood-dominated nature of the fluvial system and the short lived nature of flood events.
16. Where the suspended and bed load provenance signals do differ it can often be related to the lthological nature of the bedrock materials.

The main aims of the project have been achieved. Further work that would amplify the current findings and add to our current knowledge of the long-term evolution of river systems has been identified as:

1. Further OSL dating. The Quaternary sequence of the Rio Alias has been determined and a chronology has been established using field based correlation of the terraces of the Rio Alias and the Rio Aguas of the Sorbas basin. OSL dating has shown to be successful in the field area. As such the Quaternary sequence of the Rio Alias is prime for a detailed chronological reconstruction using OSL and U/Th dating of pedogenic carbonate. Further work would increase our understanding of the timescales involved in fluvial system response to tectonism, river-capture and eustatic sea-level change.
2. A more detailed analysis of the magnetic signals provided by each lithological unit could provide a reach-by-reach quantitative model of sediment source ascription along the modern channel.
3. SEM/petrological analysis of the terrace sequence would produce a detailed model of sediment-source ascription for the terrace sequence similar to that of the modern channel.

Appendix 1: Table to show TND equivalent mean B axis for the modern channels sediments.

Location of Sample- Modern Channel	**TND (ø)**	**Mean B axis (ø)**
Rio Alias- above the Honda confluence	-4.91	-5.12
Rambla Honda	-4.87	-5.20
Rio Alias- below the Honda confluence	-4.84	-5.15
Polopos	-5.00	-5.17
Rio Alias- above the Feos confluence	-4.91	-5.08
Rambla de los Feos	-4.97	-5.24
Rio Alias- below the Feos confluence	-4.89	-5.12
Rio Alias- downstream of Palmerosa	-4.89	-5.13
Rio Alias- above the Saltador confluence	-5.08	-5.2
Rambla del Saltador	-5.00	-5.28
Rio Alias- below the Saltador confluence	-4.94	-5.15
Coast	-5.04	-5.20

Appendix 2
Statistical analysis for OSL date obtained from Terrace D

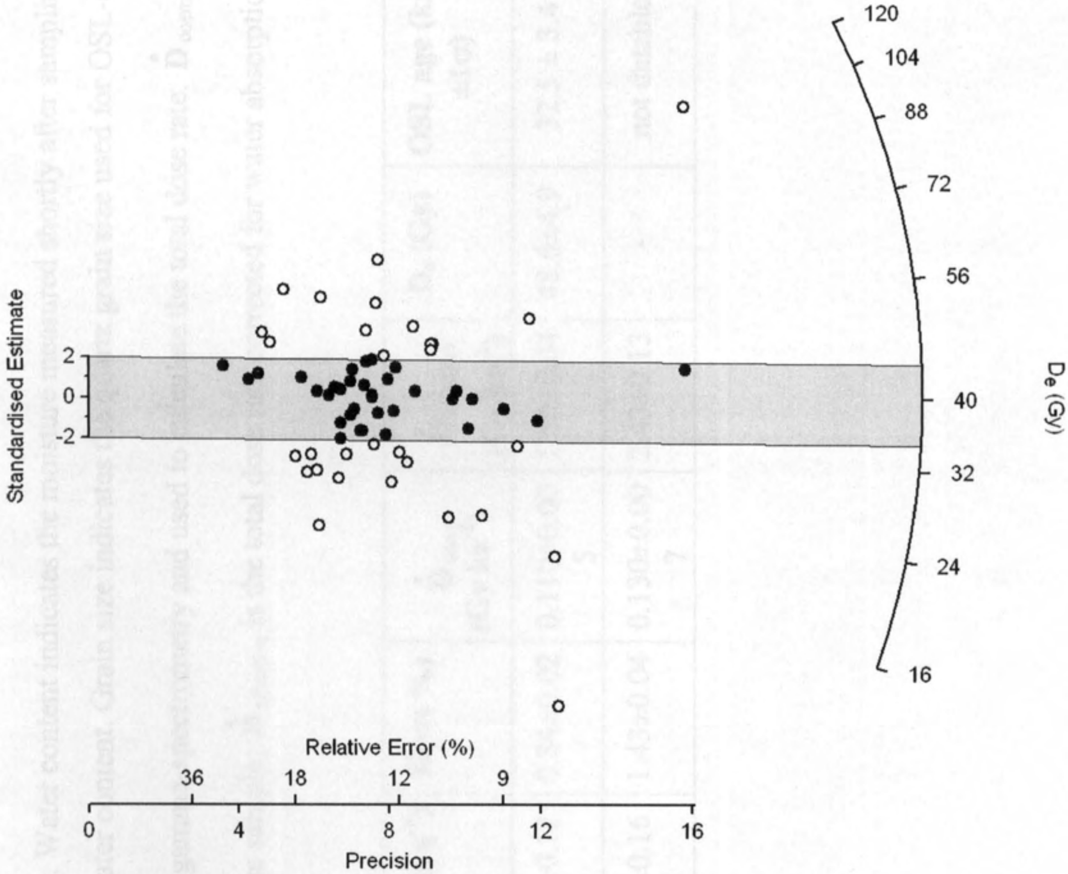

Fig. 1. A radial plot showing the individual equivalent dose values (n=50) and the related precision of LV105. The grew shadow highlights the data points (black dots) falling in the 2σ estimated range. The white dots document the overdispersion of the data set which is here 42%.

A data set is overdispersed when more than 5% of the De-values lie outside the 2σ range. Overdispersion is a quantitative measure that refers to the relative standard deviation of the De distribution of true single De values from a central De value, after having allowed for estimation of the statistical error (Galbraith et al., 1999).

Here, the high overdispersion is attributed to the OSL properties of the quartz sample (and not to the bleaching history of the sample!). The quartz OSL properties causing the overdispersion are (i) lack of sensitivity of the natural sample and (ii) dose-dependent sensitivity changes occurring during the OSL measurements.

Table 1. Analytical data used for optical dating and the dating results. Water content indicates the moisture measured shortly after sampling; its uncertainty gives the assumed maximum fluctuation of the water content. Grain size indicates the quartz grain size used for OSL-dating. U-, Th-, and K-concentrations were determined by low-level gamma-spectrometry and used to calculate the total dose rate. $\dot{\mathbf{D}}_{cosm}$ is the cosmic dose rate determined from the mean burial depth of the sample; $\dot{\mathbf{D}}_{effective}$ is the total dose rate corrected for water absorption; optical ages are given with 1σ error limits.

sample code (LV)	**origin**	**Water content**	**grain size (µm)**	**U (µg g^{-1})**	**Th (µg g^{-1})**	**K(wt %)**	$\dot{\mathbf{D}}_{cosm}$ **(Gy ka^{-1})**	$\dot{\mathbf{D}}_{effective}$ **(Gy ka^{-1})**	**D_e (Gy)**	**OSL age (ka, ±1σ)**
LV 105	terrace D	1.05±0.05	180-250	1.69±0.06	4.19±0.12	0.84±0.02	0.110±0.005	1.50±0.04	48.6±4.9	32.5 ± 3.4
LV 106	terrace C	1.05±0.05	250-300	2.26±0.08	7.18±0.16	1.43±0.04	0.130±0.007	2.43±0.13	-	not datable

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